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**IN-WELL AIR STRIPPING/BIOVENTING STUDY AT  
TYNDALL AIR FORCE BASE, FLORIDA**

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13. ABSTRACT (Maximum 200 words) This study was conducted to determine the feasibility of incorporating in-well air stripping systems into the design of bioventing systems to effectively extend bioventing to simultaneously remediate hydrocarbon contamination in both the vadose and saturated zones. The field study was conducted for 12 months between June 1994 and June 1995. The data demonstrated that the in-well air stripping systems were able to circulate the groundwater throughout the 25-foot radius of influence. The air stripping component of the systems performed well even though the air-to-water ratio could not be optimized. The well systems were shown to be effective at remediating the benzene, toluene, ethylbenzene, and xylenes (BTEX) of the hydrocarbon contamination in the groundwater within the treatment cell. The following conclusions were made: (1) the air lift pumping mechanism was capable of circulating groundwater in the aquifer; (2) the volatile compounds were effectively stripped from the groundwater; (3) anoxic groundwater entering the well was sufficiently oxygenated during air lift; (4) the residual oxygen in the off-gas from the in-well air stripping system was sufficient for supporting bioventing in the vadose zone; (5) volatile compounds in the off-gas from the well system were degraded in the vadose zone through bioventing when the mass loading did not exceed the degradative capacity of the microorganisms; and (6) bioventing was very effective for remediating residual hydrocarbon contamination in the vadose zone. Overall, the study proved that extending bioventing through incorporation of in-well air stripping was feasible and that the technology should be pursued.				
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## **PREFACE**

This report was prepared by Battelle, 505 King Avenue, Columbus, Ohio 43201, under Contract No. F08635-95-C-0064, P00042, for the Armstrong Laboratory Environics Directorate (AL/EQW), 139 Barnes Drive, Suite 2, Tyndall Air Force Base, Florida 32403-5319. The reported work was funded by the United States Air Force.

This final report describes the Coupled In-Well Air Stripping/Bioventing Study conducted at Tyndall Air Force Base, Florida; the designs of the two well systems and the bioventing system; the experimental methodologies used to monitor the technology performance; the data analysis techniques; a discussion of the significance of the experimental findings; and recommendations for future work in the development and application of the technology.

The work was performed between June 1994 and November 1995. The AL/EQW project manager was Lt. David Kuch.



## **EXECUTIVE SUMMARY**

### **A. OBJECTIVE**

This study was conducted to determine the feasibility of incorporating in-well air stripping systems into the design of bioventing systems to effectively extend bioventing and simultaneously remediate hydrocarbon contamination in both the vadose and saturated zones.

### **B. BACKGROUND**

Bioventing technology has been effectively employed at numerous U.S. Department of Defense (DoD) sites for remediating petroleum hydrocarbon contamination in vadose zone soils. The Air Force has played a crucial role in the development of the technology by supporting research and development activities that took the technology from conception to maturation. Bioventing is an effective and cost-efficient technology that exploits the activity of indigenous microorganisms to degrade contaminants in situ, thus relieving the need for excavation of contaminated soils and the permitting of off-gas emissions. This technology is the most commonly applied bioremediation technology for in situ treatment of hydrocarbon contamination.

In-well air stripping systems are being used to treat groundwater contaminated with a wide variety of contamination, with several vendors offering a number of system configurations. IEG Technologies is one of the leading vendors of in-well systems offering several configurations for different applications. IEG's coaxial groundwater circulation system (abbreviated KGB in German) is used to treat contamination in groundwater through air stripping and biodegradation and in the vadose zone through vacuum extraction. The system has been applied successfully for remediating hydrocarbon contamination.

Although bioventing and in-well air stripping have been successfully applied at sites contaminated with hydrocarbons, each technology has its limitations. Bioventing provides contaminant destruction in the vadose zone but does not address residual contamination in the groundwater. In-well air strippers are effective at transferring volatile contamination but do not provide contaminant destruction. By coupling the technologies, the in-well air stripping systems could be used to transfer the contaminants from the saturated zone to the vadose zone for destruction through bioventing.

Battelle, in conjunction with the Environics Directorate of the Air Force's Armstrong Laboratory, conducted a pilot-scale study to determine the feasibility of coupling two technologies for in situ remediation of hydrocarbon-contaminated groundwater, aquifer material, and vadose zone soils at Tyndall Air Force Base, Florida. The coupled technology joined the physical process of air stripping with the biological processes of bioventing. The final result was a process that provided in situ contaminant destruction below the ground surface. The combined technology relieves both the costs and regulatory constraints

commonly encountered with technologies that bring the contaminants above ground and require further treatment.

### **C. SCOPE**

The Coupled In-Well Air Stripping/Bioventing Study conducted at Tyndall AFB included designing a pilot-scale system with two in-well air stripping systems incorporated into a conventional bioventing system; operating and monitoring each system independently; collecting soil, soil gas, groundwater, and surface emission samples at discrete sampling times during system operation; analyzing the samples for contaminant and/or oxygen and carbon dioxide concentrations as appropriate; conducting a bromide tracer test in the groundwater to evaluate water movement; and evaluating the data to determine the performance both of the individual components and of the overall system. The two well systems included a modified bioventing well system (MBW) that was operated and monitored for the first 3 months, and a modified KGB system that was operated and monitored over the following 9 months.

### **D. RESULTS**

The data demonstrated that the in-well air stripping systems were able to circulate the groundwater throughout the 25-foot radius of influence. The modified bioventing well system developed and maintained more than 2 feet of head between the upper and lower screened sections. The estimated pumping rate of groundwater in this system was 4 L/min, based on a mass balance of the molecular weight ranges of the total petroleum hydrocarbons (TPH) around the system. The modified KGB system developed and maintained approximately 1 foot of head; however, the contaminant concentrations were too low to accurately estimate the pumping rate.

The air stripping component of the systems performed well even though the air-to-water ratio could not be optimized. The air-to-water ratio in the modified bioventing well was approximately 7, and the ratio in the modified KGB system was assumed to be similar. The analyses of the influent and effluent water and the off-gas being injected into the vadose zone showed that the volatile contaminants were removed while the heavier hydrocarbon compounds were recirculated into the aquifer. The air stripping action also was found to be effective at oxygenating the groundwater prior to recirculation. The dissolved oxygen in the influent water was consistently below 0.5 mg/L, while the level in the effluent was always above 5.0 mg/L. Although the water discharged from the well was oxygenated, the amount of oxygen delivered in the aqueous phase never met the oxygen demand between the well and the closest monitoring point.

The well systems were shown to be effective at remediating the fraction of benzene, toluene, ethylbenzene, and xylenes (BTEX) of the hydrocarbon contamination in the groundwater within the treatment cell, with a reduction of just over 40 percent in the average concentration. Profiles developed from the TPH data showed the movement of the

contamination around the treatment cell. The average TPH concentration in the groundwater actually increased by almost 30 percent over the 12 months the system was operated, possibly due to the movement of more heavily contaminated groundwater to the sampling probes.

Overall, it was difficult to determine any significant degree of remediation of the TPH in the soils below the water table. The TPH concentrations were low to begin with and, although the profiles changed, there was no net reduction in TPH concentration.

The bioventing component of the coupled technology proved successful at remediating both the residual contamination in the vadose zone and the contaminant vapors introduced in the system off-gas. The results from a surface emission test conducted in September 1994 showed that, in the warmer seasons, the oxygenation of the soils due to bioventing actually decreased the emissions of TPH vapors from the ground surface. A test conducted in January 1994 indicated that air injection increased vapor emissions. Although increased TPH emissions were detected, the flux rate was extremely low. Because the flux rate was much lower than the contribution from the off-gas from the well system, it was concluded that the bioventing component was capable of handling the TPH introduced from the well systems.

The results from the analyses of soil samples showed that the bioventing component was very effective at remediating the hydrocarbon contamination in the vadose zone. On average, BTEX and TPH concentrations were reduced by greater than 82 percent during the 12 months that the system was operated.

## **E. CONCLUSIONS**

The data collected during this study proved useful for evaluating the potential for extending bioventing to simultaneously remediate petroleum hydrocarbon contamination above and below the water table by incorporating in-well air stripping systems into the bioventing system design. Although there was no attempt to optimize the systems with regards to either pumping and/or air stripping efficiency, the following conclusions were made.

1. The air lift pumping mechanism was capable of circulating groundwater in the aquifer without the need of pumping it out of the aquifer and reinjecting it through a distribution system.
2. The volatile compounds were effectively stripped from the groundwater by the injected air during air lift and effectively transferred to the vadose zone.
3. Anoxic groundwater entering the well was sufficiently oxygenated during air lift; however, the amount of oxygen that was delivered through recirculated water could not meet the oxygen demand, and aerobic biodegradation in the saturated zone at points distant from the well was limited.

4. The residual oxygen in the off-gas from the in-well air stripping system was sufficient for supporting bioventing in the vadose zone.
5. Volatile compounds in the off-gas from the well system were degraded in the vadose zone through bioventing when the mass loading did not exceed the degradative capacity of the microorganisms.
6. Bioventing was very effective for remediating residual hydrocarbon contamination in the vadose zone.

Overall, the study proved that extending bioventing through incorporation of in-well air stripping was feasible and that the technology should be pursued.

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## LIST OF ABBREVIATIONS

AFB	Air Force Base
BDL	below detection limit
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CF	conversion factor
cfm	cubic feet per minute
CV	coefficient of variance
CO <sub>2</sub>	carbon dioxide
DO	dissolved oxygen
DoD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
FID	flame ionization detector
GC	gas chromatography
hp	horsepower
ID	identification
KGB	coaxial groundwater circulation (German abbreviation)
KVA	K-V Associates, Inc.
MBW	modified bioventing injection well
mKGB	modified coaxial groundwater circulation (German abbreviation)
MP	monitoring point
NA	not applicable? not analyzed?
ND	not detected? no data because of .....? <b>SEE TABLE FOOTNOTES!!</b>
O <sub>2</sub>	oxygen
POL	petroleum, oil, and lubricants
ppb	parts per billion
ppbv	parts per billion by volume
ppm	parts per million
ppmv	parts per million by volume

**LIST OF ABBREVIATIONS**  
**(Continued)**

psig	pounds per square inch gauge
PVC	polyvinyl chloride
TPH	total petroleum hydrocarbons
VOA	volatile organic analysis
VOC	volatile organic compounds

## **SECTION I INTRODUCTION**

### **A. OBJECTIVE**

Air stripping and bioventing are well understood, proven technologies for treating contaminated water and soil, respectively. The basic operating principle of air stripping is the mass transfer of contaminants from the aqueous phase to the gas phase through exploitation of a concentration gradient. The net result is a phase transfer of contaminant with little or no contaminant destruction. Bioventing, a more recently developed technology, has been proven effective for remediation of petroleum hydrocarbon contamination in vadose zone soils. The operating principle of this technology is the delivery of oxygen to promote the activity of indigenous microorganisms to destroy targeted contaminants in situ, relieving any requirement for ex situ off-gas treatment. The objective of the effort described in this report was to determine if air stripping could be coupled with bioventing to formulate an in situ technology capable of simultaneously remediating contamination, above and below the water table.

### **B. BACKGROUND**

Battelle, in conjunction with the Environics Directorate of the Air Force's Armstrong Laboratory, conducted a pilot-scale study to determine the feasibility of coupling two technologies for in situ remediation of hydrocarbon-contaminated groundwater, aquifer material, and vadose zone soils at Tyndall Air Force Base (AFB), Florida. The coupled technology joined the physical process of air stripping with the biological processes of bioventing. The final result was a process that provided in situ contaminant destruction below the ground surface. This combined technology relieves both the costs and regulatory constraints commonly encountered with technologies that bring the contaminants above ground and require further remediation or disposal.

In-well air stripping systems incorporate an air lift pump placed in a well casing containing two discrete screened intervals. The air lift pump, in conjunction with the double-screen design, allows for groundwater movement without pumping water to the surface and creates a groundwater recirculation cell. During air lift, the volatile contaminants are stripped out of the groundwater and transferred to the vapor phase, and the water is oxygenated prior to discharge back into the aquifer. When coupled with bioventing, the off-gas from the system is injected directly into the vadose zone to provide the oxygen necessary to support bioventing, and to deliver the stripped contaminants to the indigenous bacteria for degradation in the vadose zone. The system was monitored by regular analyses of soil gas and groundwater extracted from discrete sampling probes, and analyses of off-gas directly from the head of the well casing. The study was designed to examine the feasibility of extending the use of bioventing to simultaneously remediate contaminants in the vadose zone and below the water table.



The study was conducted at a former petroleum, oils, and lubricant (POL) site at Tyndall AFB, Florida. The site served as a fuel supply area from 1943 through 1987 (CH<sub>2</sub>M Hill, 1981). The site contained 17 tanks with a combined capacity of 491,000 gallons. JP-4 jet fuel, #2 diesel fuel, and MOGAS (motor fuel) were stored in these tanks. Several of the tanks developed leaks resulting in soil and groundwater contamination at the site.

The system was located in an area of POL-B at Tyndall AFB, Florida, that was characterized during a soil gas survey as having low oxygen (O<sub>2</sub>) and high carbon dioxide (CO<sub>2</sub>) and total petroleum hydrocarbon (TPH) concentrations. The system was installed in June 1994 and was operated for 12 months. Initial soil, soil gas, groundwater, and surface emission samples were collected and analyzed, and the data served as the baseline against which the system performance was evaluated. Three subsequent sets of soil gas and groundwater samples were collected during system operation. Two additional sets of surface emission samples were collected, the first after 3 months of operation and the second after 6 months of operation. A second set of soil samples was collected following 12 months of operation. A bromide tracer test was conducted at startup to track groundwater movement within the system radius of influence.

### C. SITE DESCRIPTION

Tyndall AFB is located in the central part of the Florida panhandle and is part of the eastern Gulf of Mexico sedimentary basin. The uppermost sediments of the region are made of sands and gravel which are approximately 100 feet thick. These sediments are moderately permeable and transmit water readily. However, occasional clayey sand and hardpan layers occur at varying depths within the formation resulting in the impediment of downward groundwater movement.

From 100 feet to approximately 330 feet deep, poorly cemented shell beds of the Intracoastal Formation are present. This layer contains abundant fossils, quartz sand, and calcium carbonate grains that are cemented by crystalline calcite and clay. The upper portion of the formation is relatively impermeable, whereas the lower portion is highly permeable. Below 330 feet and to a depth of approximately 600 feet, permeable limestone deposits are present.

Rainfall on the Tyndall AFB peninsula either percolates into the ground directly or flows across the ground surface into water bodies surrounding the peninsula. Rainfall that percolates into the ground is stored temporarily in the water table aquifer. The 100-foot-thick aquifer is composed of fine-to-coarse sand and has a surface that rises during periods of heavy rainfall and declines during periods of low rainfall. Annual fluctuations of approximately 5 feet are typical. The average depth to groundwater varies from about 1 to 10 feet over most of the base, but may be as deep as 15 feet in some areas. The slope of the water table is relatively flat throughout the base and groundwater movement typically follows the slope of the overlying terrain, flowing in a northeast and southwest direction from a high

near the coastal ridge. POL-B lies on the northern side of the divide, and the direction of groundwater movement is to the northeast.

A second aquifer system occurs at approximately 250 feet below sea level and is a confined system named the Floridian aquifer. It consists of limestone and dolomites and is approximately 1,100 feet thick, but potable water is derived only from the upper 250 to 500 feet of the aquifer.

#### **D. SCOPE**

The scope of the Coupled In-Well Air Stripping/Bioventing Study conducted at Tyndall AFB included designing a pilot-scale system with two in-well air stripping systems that were incorporated into a conventional bioventing system; operating and monitoring the system for 12 months; collecting soil, soil gas, groundwater, and surface emission samples at discrete sampling times during system operation; analyzing the samples for contaminant and/or oxygen and carbon dioxide concentrations as appropriate; and evaluating the data to determine the performance both of the individual components and of the overall system. The two well system included a modified bioventing well system (MBW) that was operated and monitored for the first 3 months, and a modified KGB system that was operated and monitored over the following 9 months.

## SECTION II METHODOLOGY

### A. PRELIMINARY SITE CHARACTERIZATION

A soil gas survey was conducted at site POL-B at Tyndall AFB (Figure 1) from February 21 through February 24, 1994. A sampling grid was established based on a 20-foot interval in the northwest corner of the site (Figure 2). Soil gas samples were extracted at each node of the grid from depths between 1½ and 4 feet and analyzed for O<sub>2</sub>, CO<sub>2</sub>, and TPH. The gas was extracted through stainless steel K-V Associates, Inc. (KVA) probes using a ¼-hp Gast vacuum pump. Approximately 1 liter of the extracted gas was collected in Tedlar™ bags for analysis. The O<sub>2</sub> and CO<sub>2</sub> concentrations were measured using a GasTech Model 3252OX O<sub>2</sub>/CO<sub>2</sub> meter. The TPH was measured using a TraceTechtor™ meter calibrated against a hexane standard. The results from the soil gas analysis are presented in Table 1.

Following the completion of the soil gas survey, groundwater samples were collected from areas showing elevated levels of TPH. The sampling grid locations are shown in Figure 2. The groundwater was collected through either a sacrificial air sparging tube or a KVA probe, using a peristaltic pump. The sparging tubes were driven to approximately 1 foot into the groundwater at approximately 6 feet below ground surface using a demolition hammer. The volume of the tube was purged prior to collecting the sample. The samples were put on ice and shipped over night to an analytical laboratory for analysis of benzene, toluene, ethylbenzene, and xylenes (BTEX). The results from these analyses are presented in Table 2.

The data from the soil gas survey delineated a contaminated area characterized by depressed O<sub>2</sub> levels and elevated CO<sub>2</sub> levels. This area was located around Sampling Node 21. The TPH concentration in the soil gas extracted from approximately 4 feet below grade at Node 21 was 10,600 ppm. The O<sub>2</sub> concentration in the gas from this node was 2 percent and the CO<sub>2</sub> concentration was 14.2 percent. This trend of depressed O<sub>2</sub> and elevated CO<sub>2</sub> is a positive indicator of microbial activity, and the levels found at Node 21 suggest that the activity of the indigenous bacteria was O<sub>2</sub> limited. This suggested that bioventing would be an attractive and effective remediation technology for enhancing the microbial destruction of the contaminants in this area of POL-B.

The data from the groundwater samples also revealed significant contamination in proximity to Sampling Node 21. TPH was measured in the sample from Sampling Node C (10 feet away from Node 21) at 3,200 mg/L. BTEX constituents were measured at 53, 130, 290, and 1,400 µg/L for benzene, toluene, ethylbenzene and xylenes, respectively. The concentrations of the BTEX constituents relative to the TPH indicated that this site would be a very good candidate for a demonstration/treatability study to examine the effectiveness of an in-well air stripping system for remediation of the volatile fraction as well as the heavier, less volatile contaminants.

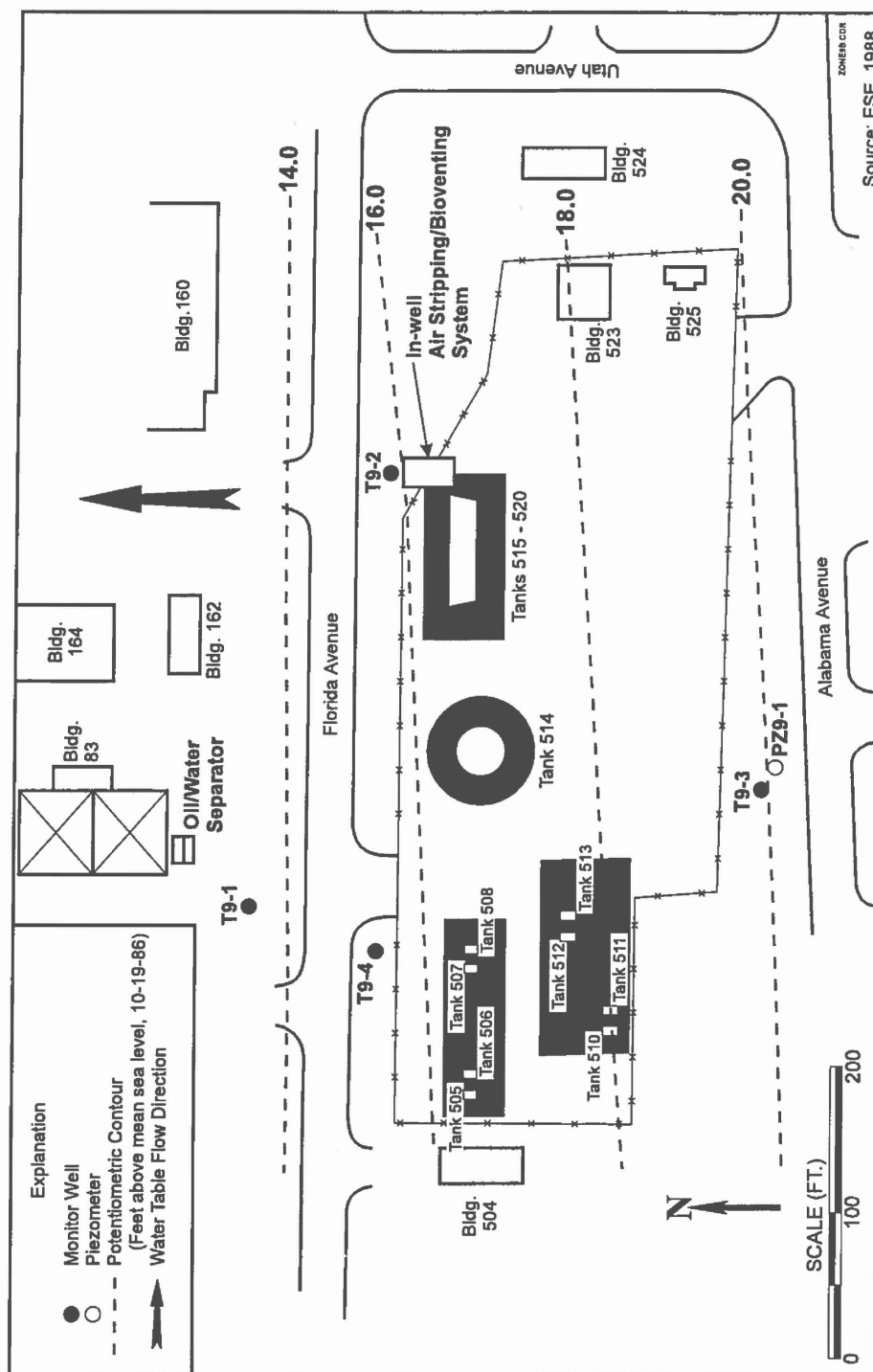
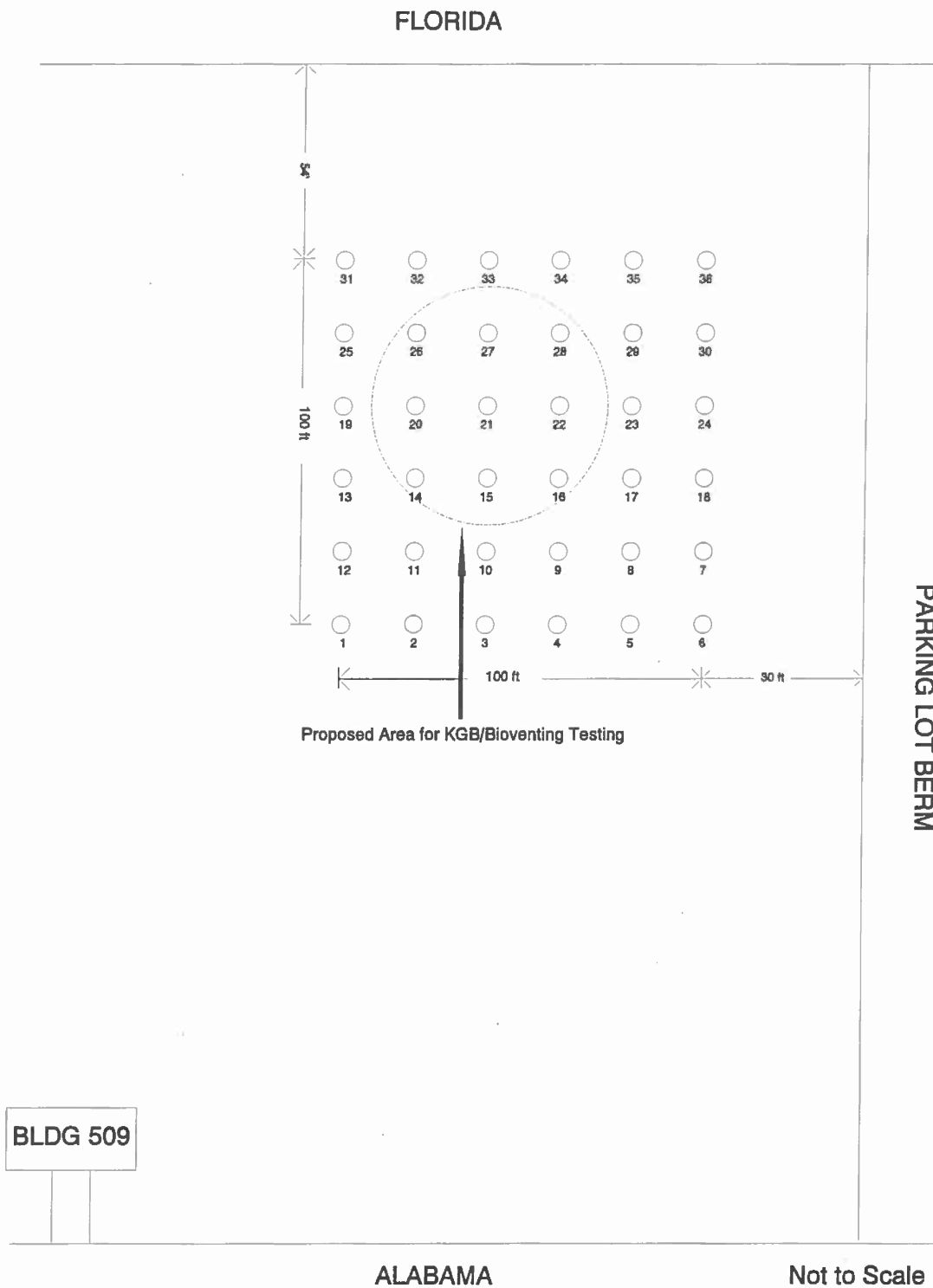


Figure 1. Map of POL.B at Tyndall AFB Showing Historic Locations of Tanks and Location of the Study.



**Figure 2. Sampling Grid Location Used to Conduct the Soil Gas Survey and Collect Representative Groundwater Samples.**

**TABLE 1. SOIL GAS ANALYSIS RESULTS**

Point	Depth (feet)	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	TPH (ppm)	Point	Depth (feet)	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	TPH (ppm)
1	2.0	19.0	2.9	140	18	2.5	19.3	3.0	160,140
1	4.0	20.0	0.0	200	19	2.0	20.7	0.6	64
2	2.0	19.5	1.5	90	20	2.0	20.0	1.5	64
2	3.0	18.5	1.0	94,99	21	0.0	14.2	2.0	5,300
3	2.0	19.0	1.3	99	24	2.0	0.0	14.2	>10,600
3	3.0	20.0	0.5	200	22	1.5	20.5	0.6	50
4	--	--	--	--	23	2.0	17.5	2.8	110
5	2.0	11.0	6.5	600	24	2.0	19.5	1.7	74
5	3.0	21.0	0.0	160	28	2.0	20.5	0.5	42
6	2.0	0.0	12.5	2,600	26	2.0	20.5	1.05	105
6	3.0	13.0	6.2	2,400	27	2.0	18.0	2.7	120
1	3.0	17.5	3.5	500	28	2.0	19.2	1.6	110
7	2.5	20.5	0.1	64	29	2.0	9.5	6.1	680
8	2.5	20.5	0.1	72	20	2.0	9.5	6.1	1,360
9	2.5	20.0	0.5	100	30	1.5	17.0	2.5	130
10	2.5	20.0	0.5	34	31	2.0	20.9	0.5	99
11	2.5	20.8	0.0	28	32	2.0	20.5	0.6	65
12	2.5	20.8	0.0	64	33	2.0	20.5	0.5	63
13	2.5	14.9	3.5	180	34	2.0	5.8	7.1	4,400
14	2.5	--	--	200	34	2.0	5.8	7.1	8,800
15	2.5	--	--	80	35	2.0	15.0	4.2	420
16	2.5	13.3	5.9	180	36	2.0	19.0	1.7	
17	2.5	19.0	2.1	110					

**TABLE 2. GROUNDWATER DATA**

Sample	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	Xylenes (µg/L)	TPH (mg/L)
SG-5	8.4	<5.0	14.0	31.0	9.2
SG-6	820.0	320.0	290.0	900.0	5.7
SG-13	<5.0	<5.0	5.2	<15.0	<1.0
SG-16	<5.0	5.3	6.1	21.0	3.1
SG-21	34.0	5.9	27.0	130.0	<1.0
SG-28B	<5.0	6.0	5.1	<15.0	--
SG-37	37.0	6.2	24.0	130.0	--
SG-A	<5.0	5.8	5.5	17.0	140.0
SG-B	<5.0	5.5	<5.0	<15.0	<15.0
SG-C	53.0	130.0	290.0	1,400.0	3,200.0
SG-D	<5.0	7.1	<5.0	<15.0	<2.0
Blank	<5.0	<5.0	<5.0	<15.0	<1.0

SG-# Sample grid location.

-- Sample lost in transit.

The objective of conducting the demonstration/treatability study of coupling the in-well air stripping and bioventing technologies was to simultaneously remediate the contamination in the vadose zone along with the contaminants both in the groundwater and associated with the aquifer solids. The results from the soil gas survey showed that the levels of vadose zone contamination and microbial activity in the area were sufficient to support the bioventing part of the study. The groundwater data showed that the levels of contaminant below the water table were sufficient to support the in-well air stripping part of the study.

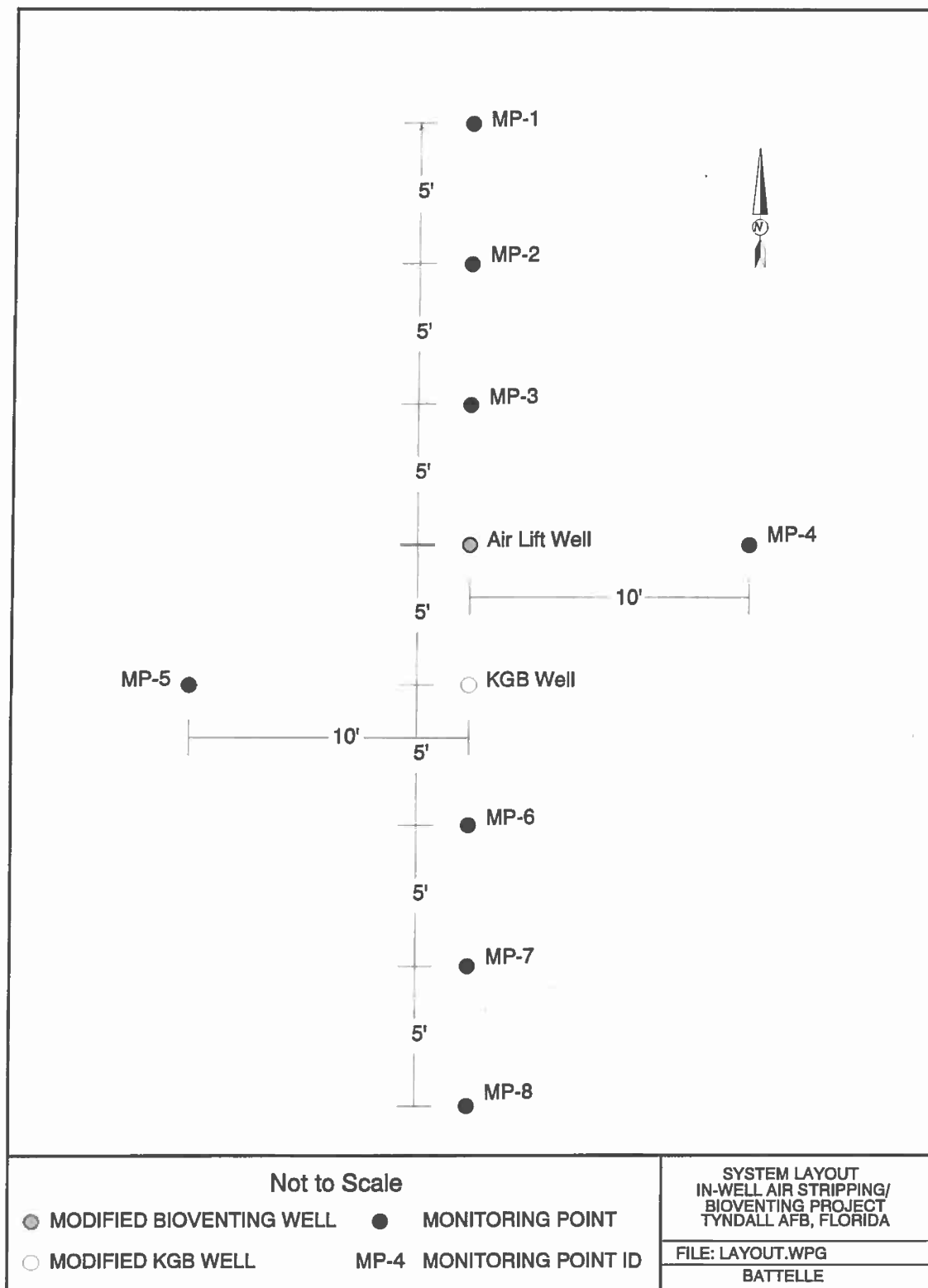
## **B. SYSTEM DESIGN AND INSTALLATION**

The system utilized in this study consisted of two independent in-well air stripping systems, a series of soil gas and groundwater sampling probes, an air compressor and air flowmeter, and several thermocouples for recording soil and groundwater temperatures. The first in-well air stripping system (mKGB) was a modification of IEG Technology Corporation's KGB system (from the German for coaxial groundwater circulation). The second in-well air stripping system was a modified bioventing injection well (MBW) system. The purpose of incorporating in-well air stripping system into bioventing systems was threefold:

- To test the potential for using an in-well air stripping system to transfer contaminants from the groundwater to the vadose zone.
- To provide oxygen to the microorganisms in the vadose zone for supporting bioventing to promote aerobic degradation of the introduced and residual contamination in the vadose zone.
- To aerate the recirculating groundwater to provide oxygen to microorganisms that aerobically degrade contaminants in the saturated zone.

### **1. System Layout**

The system was designed so that the well systems were in the center of a network of monitoring probes (Figure 3). The well systems were placed 5 feet apart along the central axis of the overall system. Eight soil gas/groundwater monitoring points (MPs) were installed. Three points were installed along the central axis on each of the opposite sides of the well systems. These points were spaced at 5-foot intervals. One soil gas/groundwater monitoring point (MP-4) was installed 10 feet from the MBW system on the eastern side of the system perpendicular to the central axis. Another soil gas/groundwater monitoring point (MP-5) was installed 10 feet from the modified KGB system on the western side of the system perpendicular to the central axis.



**Figure 3. Layout of the In-Well Air Stripping/Bioventing System at Tyndall AFB, Florida.**



The monitoring points were placed so that contaminant, oxygen, and carbon dioxide concentrations could be monitored over both the lateral and vertical extent of the vadose and saturated zones within the expected sphere of influence from each of the well systems.

## **2. Monitoring Point Design and Installation**

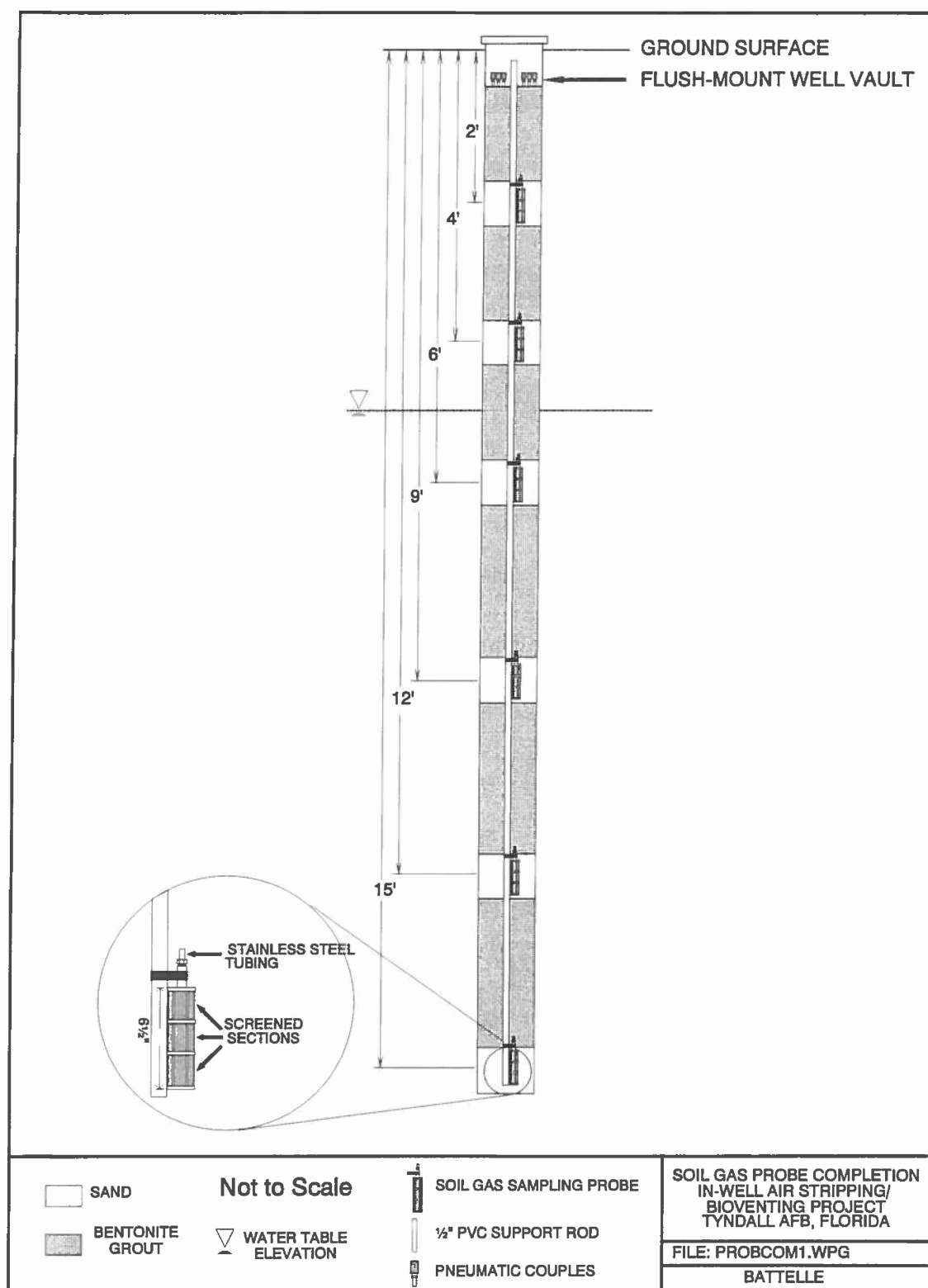
The monitoring system was designed to allow soil gas and groundwater sampling and soil and groundwater temperature monitoring. The eight soil gas/groundwater monitoring points were installed using a hollow-stem auger and were completed as shown in Figure 4. The sampling probes each consisted of a 6-inch screened suction strainer filled with pea gravel. The probes were connected to ¼-inch stainless steel tubing fed to a flush-mount well vault installed at the ground surface. A female pneumatic coupling was connected to the end of the tubing so that the soil gas and groundwater sampling equipment could be easily connected. The soil gas probes were set at 2 and 4 feet below ground surface (bgs) and the groundwater probes were set at 6, 9, 12, and 15 feet bgs. The monitoring points were designated MP-1 through MP-8 (see Figure 2).

## **3. Modified KGB System Design**

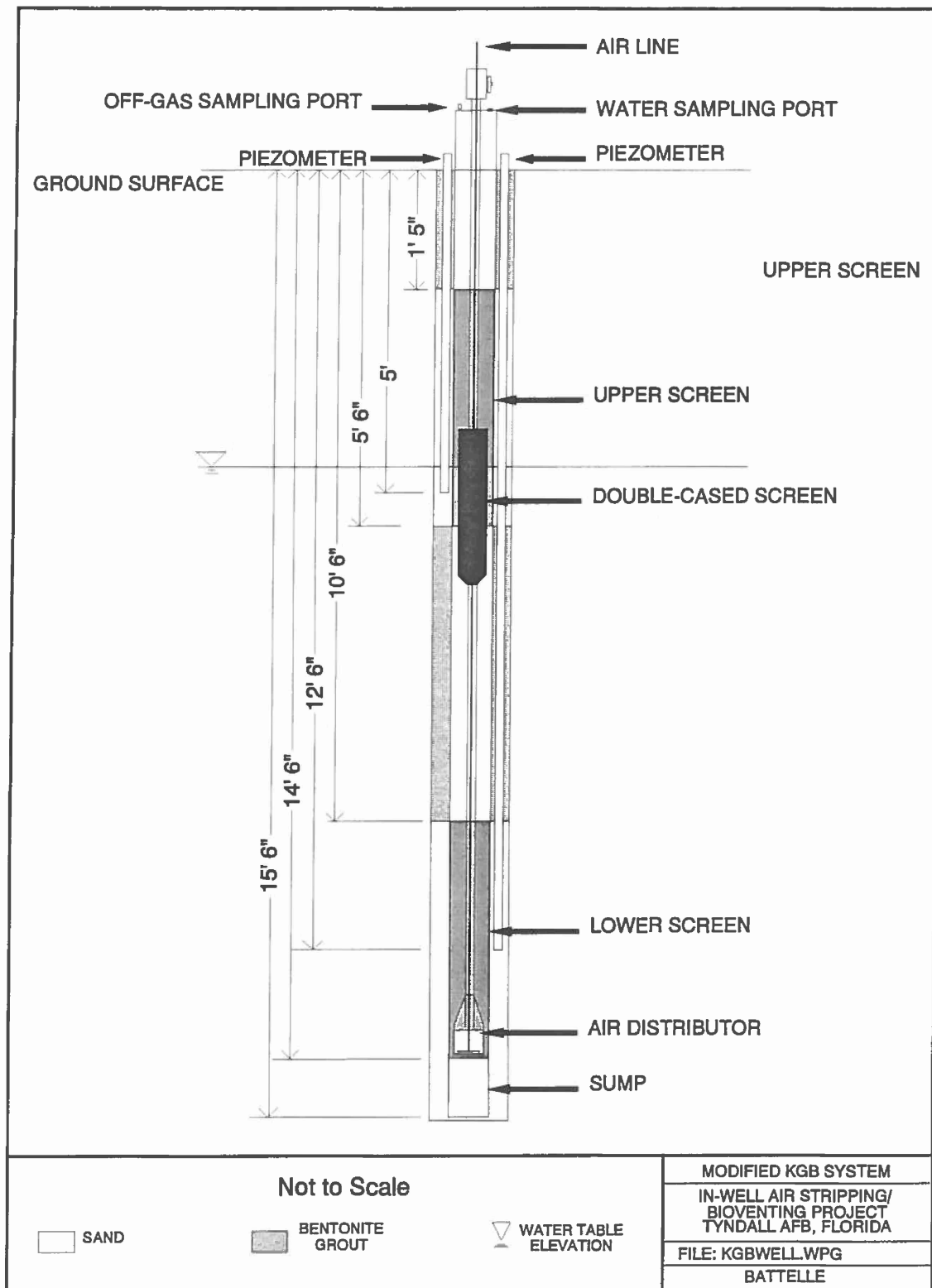
IEG Technology Corporation's KGB system has been demonstrated successful for remediating soil and groundwater contamination by combining in situ air stripping with soil vapor extraction. The KGB system typically includes an air compressor to inject clean air into an air distributor placed below the static water level and create an air lift that drives the water recirculation around the system. A vacuum is pulled on the head of the well to recover the contaminated vapors resulting from the stripping action and to facilitate air movement in the vadose zone with subsequent extraction of the vapors through the KGB system. The vapors are then treated above ground prior to off-gas release.

The KGB system used at Tyndall AFB was modified to replace the soil vacuum extraction component with bioventing to provide in situ destruction of the contaminant (Figure 5). The residual oxygen in the vapor from the system was to serve as the source of oxygen to support bioventing.

The modified KGB (mKGB) system was installed using a 12-inch hollow-stem auger by drilling to a depth of 16 feet. An 8-inch-diameter polyvinyl chloride (PVC) well case was inserted in the center of the augers. The well case consisted of a 12-inch sump, a 5-foot screen section (0.020 slot) a 5-foot riser section, a 4-foot screen section, and another 5-foot riser section. The casing was set so that the upper screen would straddle the water table to allow groundwater recirculation and vapor discharge to the vadose zone. Five 1-inch-diameter PVC piezometers were inserted in the annular space between the inner wall of the auger and the PVC well casing. Four of the piezometers were equally placed around the casing and set so that the bottom of the piezometer were 6 inches above the bottom of the upper screen one piezometer was set so that the bottom of the piezometer was at the middle of the lower screen.



**Figure 4. Design and Completion of the Soil Gas/Groundwater Monitoring Points Used on the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.**



**Figure 5. Design of the Modified KGB System Used in the In-Well Air Stripping/Bioventing Study at Tyndall AFB.**

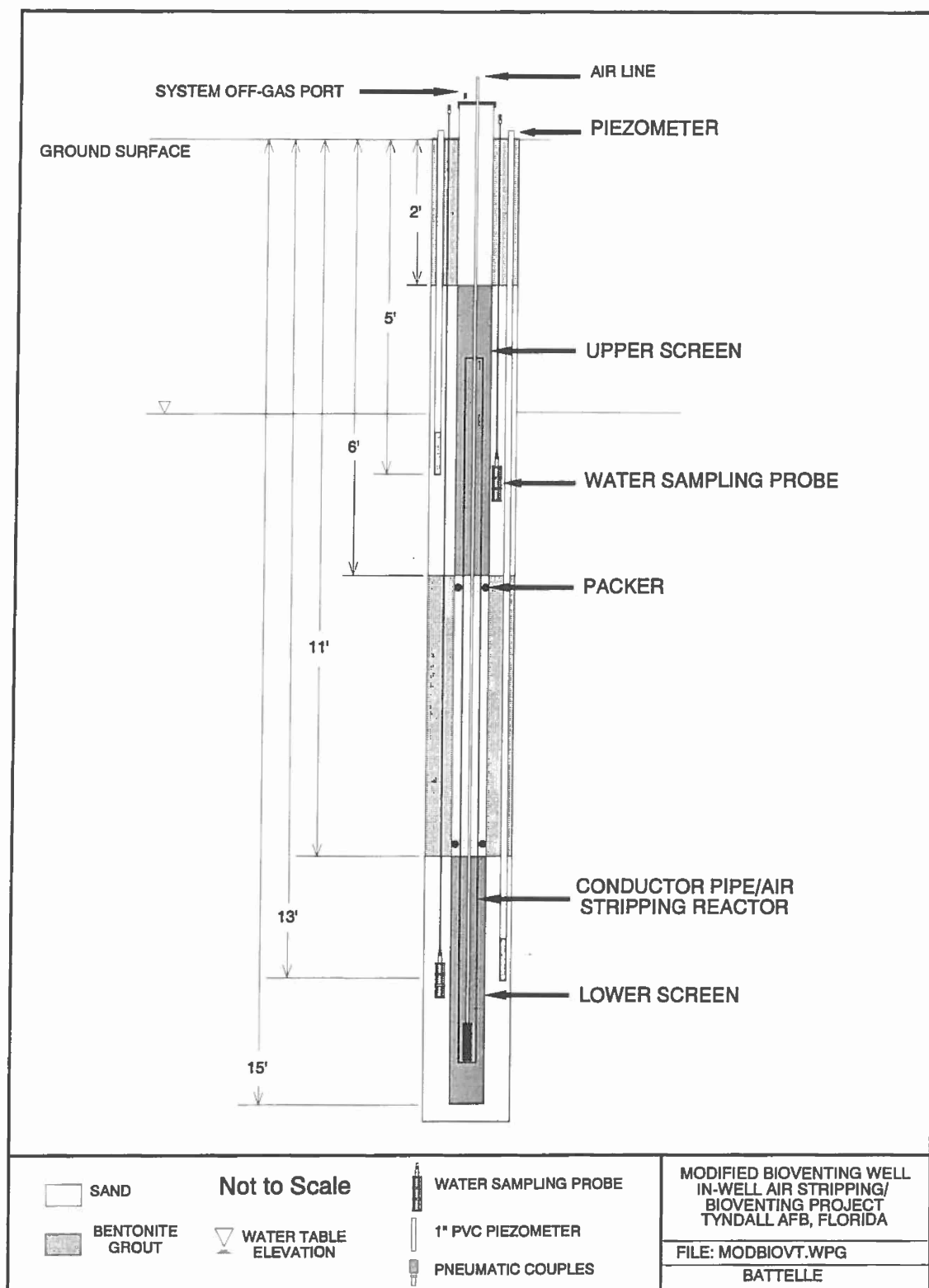
The KGB system was installed in the well so that the air distributor was set at the bottom of the lower screen. A double-cased screen was set at the water table interface to facilitate gas and water separation. An 8-inch-diameter sanitary well seal was installed at the top of the casing both to seal the well and to hold the KGB system in place. A soil gas sampling port and a water sampling port were installed in the sanitary seal. The air supply line was fitted with pneumatic couplings and connected to an air compressor.

#### **4. Modified Bioventing Well Design**

A 4-inch-diameter PVC bioventing well was modified by extending the well deeper into the groundwater, incorporating a dual screen design into the well casing, and installing an air lift pump/air stripping system inside the well casing (Figure 6). The MBW system was constructed above ground prior to installation. A 6-inch hollow-stem auger was used to drill to a depth of 15½ feet. The MBW system was placed into the center of the auger. As the augers were pulled out, the sand pack and bentonite seals were completed.

The MBW system was completed so that the lower screen extended from 11 to 15 feet bgs and the upper screen was set between 2 and 6 feet bgs to straddle the water table. Four 1-inch-diameter PVC piezometers were set at 5½ feet bgs and one was set at 13 feet bgs to monitor the head that developed around the system. Groundwater sampling probes were installed at 5½ and 13 feet bgs to collect effluent and influent water samples, respectively.

The air lift/air stripping system consisted of an air supply distributor in a 10-foot-long, 2-inch-diameter PVC conductor pipe. The conductor pipe was set so that it extended between 4½ and 14½ feet bgs. The air distributor was set inside the conductor pipe just above the bottom opening. Conductor pipe was held in place using two stainless steel compression packers. The top of the well was fitted with a 4-inch-diameter sanitary seal that served to seal the system and hold the air supply line in place. A system off-gas sampling port was installed in the sanitary seal.



**Figure 6. Design of the Modified Bioventing Well System Used During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.**

## **C. SAMPLING**

### **1. Soil Sampling**

Soil samples were collected in June 1994 during installation of the in-well air stripping and bioventing systems. The data from this sample set served as the baseline against which to evaluate the performance of the system for removing contaminants from both saturated and vadose zone soils. A second set of soil samples was collected in June 1995, after the project activities had been completed at the study site. The data from these samples were used to quantify the removal efficiency of the in-well air stripping systems in the saturated zone and the bioventing component in the vadose zone.

The initial soil samples were collected during installation of the soil gas and groundwater monitoring points. The samples were collected in brass sleeves using a split-spoon technique. A 4-inch hollow-stem auger was used to drill the holes in which the monitoring points were installed. The split-spoon sampler was advanced ahead of the auger during the drilling process to collect undisturbed soil samples. Spoon samples were collected from 4 to 6 feet, 8 to 10 feet, and 12 to 14 feet bgs. The spoon was retrieved and split open, and the sleeves were immediately capped and sealed. The sleeves were labeled, put on ice, then shipped via overnight delivery to Battelle in Columbus, Ohio, for analysis. Upon receipt at the laboratory, the samples were logged and were stored at 4°C until analysis. All soil samples were analyzed within 14 days of collection. Chain-of-custody forms accompanied the samples, and the sampling activities were documented in the field record books.

The final set of soil samples were collected using a GeoProbe™ soil coring device. Samples were collected at a distance of approximately 1 foot from the monitoring points from depths of 4 to 6 feet, 8 to 10 feet, and 12 to 14 feet bgs. A 4-foot core barrel with a liner insert was driven from 1 foot above to 1 foot below the desired interval. Because the core often came up partially full, the length of soil core in the insert was measured to determine the depth represented by the retrieved soil. The desired interval was cut from the 4-foot core and sealed, labeled, put on ice, then sent via overnight delivery to Battelle for analysis. The samples were logged in upon receipt and stored at 4°C until analysis. All samples were analyzed within 14 days of collection. Chain-of-custody forms accompanied the samples, and the sampling activities were documented in the field record books.

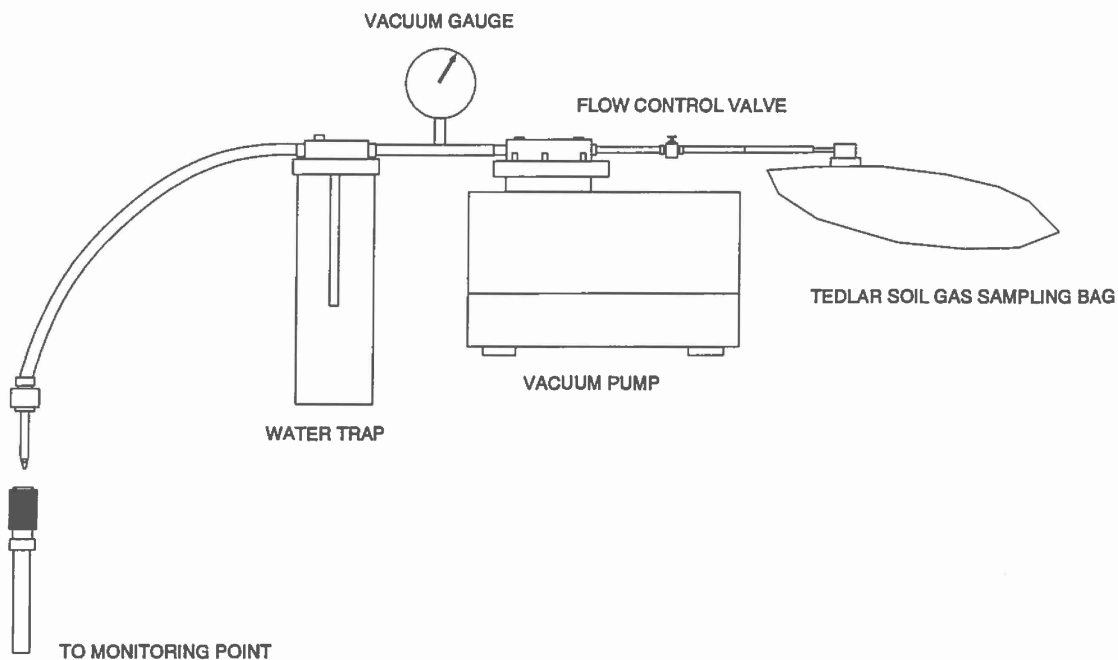
### **2. Soil Gas Sampling for Field Analyses**

Soil gas samples were collected during the Coupled In-Well Air Stripping/Bioventing Study to monitor the concentrations of volatile organic compounds (VOCs), O<sub>2</sub>, and CO<sub>2</sub>. The movement of gas-phase organics within the soil can be used to indicate both the radius of influence of air injection into the vadose zone and the reduction of organics which may indicate the accelerated degradation of fuel-related compounds. Tracking soil gas

quality was one factor in identifying the level of biodegradation achieved by the systems evaluated.

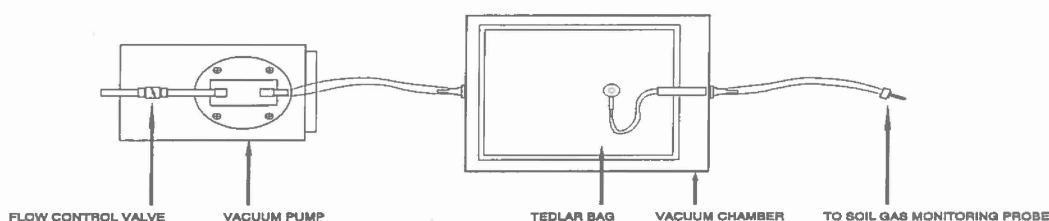
Eight 2-level soil gas monitoring points were installed at the demonstration site in the vadose zone. These points allowed the extraction of gas samples from depths of 2 feet and 4 feet bgs. The limited number of sampling depths was dictated by the shallow groundwater table at approximately 5 feet bgs.

Soil gas samples were extracted from the monitoring points at the 2-foot and 4-foot depths and analyzed in the field to monitor both the effectiveness of the well systems for supporting bioventing and respiration in the vadose zone. The soil gas samples were collected in Tedlar™ gas sampling bags. Initially, the gas sample was pulled through the pump into the Tedlar™ bag as shown in Figure 7. The sampling pump was equipped with a water trap to prevent water from entering the pump in the event that water table had risen and the soil gas probes were submerged in groundwater. This sampling system required pulling large volumes of soil gas to flush the trap before collecting samples. Additionally, the trap had a tendency to leak, thus interfering with the O<sub>2</sub>, CO<sub>2</sub>, and TPH measurements.



**Figure 7. Schematic of the Apparatus Originally Used to Collect Soil Gas Samples During the In-Well Air Stripping/Bioventing Study.**

To overcome the large volume purging requirement and potential interferences associated with the trap, a device was constructed that allowed for direct collection of soil gas (Figure 8). A Teflon™ line connected the gas sampling bag directly to the quick-disconnect coupling at the end of the tubing from the soil gas probe. The bag was placed in a chamber and a vacuum was pulled using the Gast pump. Evacuating the chamber caused the soil gas to be drawn from the monitoring point, inflating the Tedlar™ bag. The vacuum was applied slowly to avoid pulling water into the gas sampling bag. One bag volume (1 liter) of soil gas was pulled and discarded to flush out the probe and associated tubing. A second bag volume was then collected for analyses. The soil gas in the bag was analyzed for O<sub>2</sub>, CO<sub>2</sub>, and TPH using field instruments.



**Figure 8. Schematic of the Soil Gas Sampling Apparatus Used to Collect Samples Directly into Tedlar™ Bags.**

### **3. Soil Gas Sampling for Laboratory Analyses**

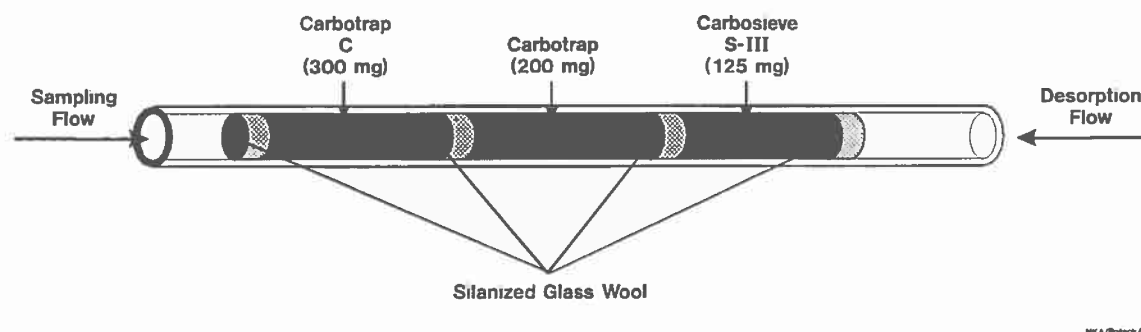
The soil gas samples were collected and transported to a facility where qualitative and quantitative analyses, by gas chromatography (GC), could be performed to identify the organic compounds in the soil gas.

Soil gas samples are collected using several different techniques, depending on the expected organic concentrations in the sample. If low levels (parts per billion by volume) are anticipated, then tubes packed with sorbent materials are appropriate. These allow large volumes of soil gas to be collected onto a single sampling medium which permits a preconcentration of organics that makes quantitation possible. This is the preferred sampling method for surface emission samples where low concentrations are expected. Tubes also can be used for high-concentration sampling if small soil gas volumes are collected. Alternatives to sorbent tubes include evacuated air sampling canisters, Tedlar™ bags, or syringe samples that permit collection of "whole air samples." In all cases, the



collection devices would be returned to an analytical facility equipped with instrumentation designed to process such samples.

Collection of soil gas samples at Tyndall AFB was performed using the sorbent tube methodology. To efficiently capture the JP-4 constituents, a three-phase carbon-based sorbent bed (Supelco, Carbotrap™ 300, Catalog No. 2-0370) was employed (Figure 9). This sorbent trap has been evaluated extensively at Battelle (Pollack and Gordon, 1993) in conjunction with ambient air sampling and has been shown to be very efficient at capturing and retaining a wide range of VOCs. This carbon-based sorbent bed typically displays very low background artifact levels. The sorbent configuration does have limitations in that it is not able to retain methane, ethane, and ethylene at ambient temperatures.



**Figure 9. Schematic Showing the Order of Packing of the Sorbents in the Sorbent Tubes Used to Collect Gas Samples for GC Analyses.**

Soil gas samples were pulled through the sorbent trap using a personal monitoring pump (SKC, Model 224-PCXR7) such that the air passed from the weakest sorbent (Carbotrap C) to the moderately strong material (Carbotrap) and finally onto the strongest sorbent (Carbosieve™ S-III). This three-phase arrangement made it possible to capture a wide molecular weight range of VOCs while still allowing efficient desorption. Tube desorption was accomplished by backflushing the organics off the sorbent bed with helium while heating the tube.

The sorbent tubes were preconditioned for sampling by baking each tube at 350°C for 1 hour with an ultra-high-purity helium purge flow of 50 cm<sup>3</sup>/minute. This ensured that the sorbents were clean before their use.

Because sample concentrations were anticipated to be in the parts per million by volume range, a 50-cm<sup>3</sup> sample volume was collected. Prior to sampling from a monitoring

point, a personal monitoring pump (SKC Model 224-PCXR7) was connected to the soil gas sample fitting and allowed to draw for 3 minutes. The soil gas volume was collected to flush the subsurface sample tubing and to ensure that a representative soil gas sample would be available for collection. The influent end of the sorbent tube was fitted with a quick-disconnect fitting and the other end was connected to the SKC pump which had been calibrated to draw air at a flow rate of 50 cm<sup>3</sup>/minute. The sorbent tube was connected to the sampling point and the pump was operated for 1 minute, resulting in a 50-cm<sup>3</sup> soil gas sample being drawn through the sorbent tube. After sampling, the tube was disconnected from both the pump and the sampling point, capped, and returned to its shipping container. The container was labeled to identify the sampling site, date, and time. This same information was recorded in the field notebook. This procedure was repeated at the remaining sampling locations.

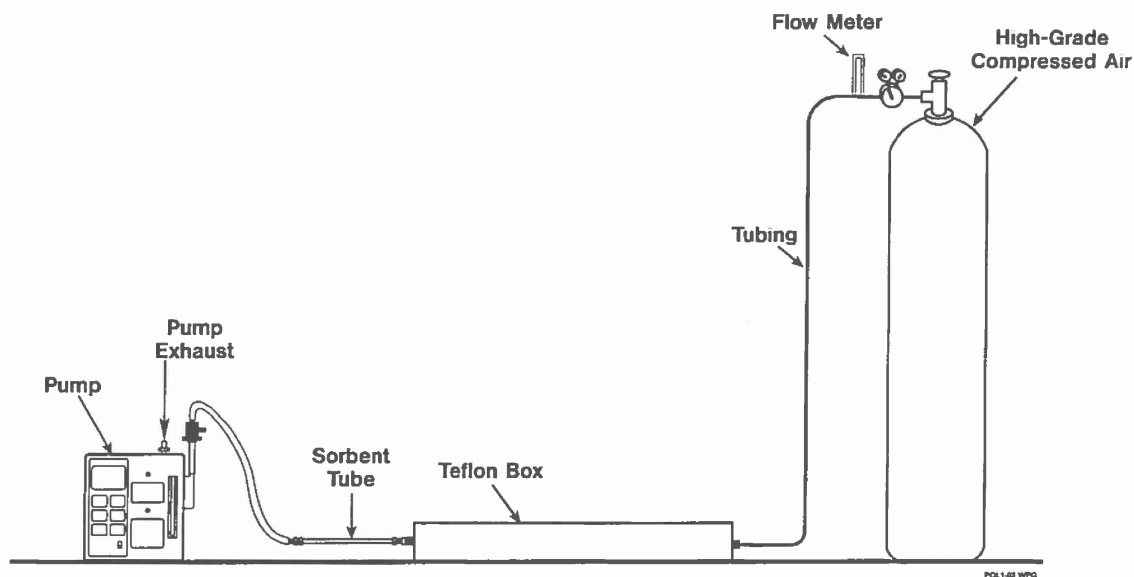
In addition to these soil gas samples, off-gas samples from the MBW and mKGB systems, duplicate soil gas samples, ambient air samples, and trip blanks were collected for quality assurance data. The tubes were shipped to the laboratory at Battelle via overnight delivery. Upon receipt, the tubes were logged and stored for analysis. All tube samples were analyzed within 21 days of collection.

#### **4. Surface Emission Sampling**

One concern over the implementation of air injection as a means of groundwater and soil remediation is the possibility of transferring a terrestrial contamination problem to the atmosphere during air stripping of organics. To determine if there was atmospheric loading of VOCs from the Coupled In-Well Air Stripping/Bioventing Study at Tyndall AFB, surface emission measurements were made.

An area of soil was enclosed under an inert box designed to allow the purging of the enclosure with high-purity air. The purging activity removed ambient air from the region above the soil and allowed an equilibrium to be established between hydrocarbons emitted from the soil and the organic-free purge air (Dupont, 1987). The air stream was sampled by drawing a known volume of the resulting hydrocarbon/pure air mixture through a tube packed with sorbent materials. The sorbents retained organics associated with soil surface emissions. The sample tube was then shipped to Battelle where the sorbents were thermally desorbed and the organics were resolved and quantified by GC. These measured concentrations were then converted to a flux measurement value that indicated emission rates for targeted hydrocarbons from the soil to the atmosphere.

The sampling system used at Tyndall AFB is shown in Figure 10. The system includes a Teflon™ box covering a surface area of 0.453 m<sup>2</sup> that was fitted with both inlet and outlet ports for entry and exit of the high-purity purge gas. Inside the box is a manifold that delivers an air supply uniformly across the soil surface. The same type of manifold was also fitted to the exit port of the box. This configuration delivers an even flow of air across the soil surface under the box so that a representative sample is generated. The surface



**Figure 10. Schematic of the Apparatus Used to Monitor Surface Emissions.**

emission sampling system is inert, employing components of either Teflon™ or stainless steel, to ensure that no organics enter or leave the air stream.

During surface emission sampling, the Teflon™ box was positioned at 5½-, 12½-, and 25-foot distances to the west of the two in-well air stripping systems. The collection of each surface emission sample involved the following activities:

- a. Ensure that the sorbent tubes have been conditioned by thermally desorbing any residual compounds at 350°C for 60 minutes using a pure helium flush.
- b. Set the flow of the SKC pump to ~50 cm<sup>3</sup>/minute using a Mini-Buck™ gas flow calibrator (Model APB-M5). Connect the Mini-Buck™ calibrator to the inlet end of a spare sorbent tube and the outlet end of this tube to the SKC pump. The pump flow is again adjusted so that the air flow through the tube is 50 cm<sup>3</sup>/minute. Remove the sorbent tube and measure the pump flow again. This is the flow rate necessary to pull 50 cm<sup>3</sup>/minute through the packed tube (in the range of ~60 cm<sup>3</sup>/minute). The sorbent tube used for this flow rate adjustment is not used for sampling.
- c. Install a pressure regulator and flowmeter to the high-purity air cylinder and set a flow rate of 2 L/minute, once again using the Mini-Buck™

calibrator to confirm this rate. Cylinder delivery pressure was at ~60 psig prior to setting this flow.

- d. Check all the tubing and fittings on the Teflon™ box. Repair or replace as necessary.
- e. Position the Teflon™ box at the location where the sampling is to be done. It is necessary to loosen the soil and remove ground cover around the perimeter of the box to allow it to be in continuous contact with the soil. However, the surface of the soil is disturbed as little as possible during this process.
- f. Connect the inlet port on the Teflon™ box to the air cylinder via Teflon™ tubing and start a 2-hour purge to obtain equilibrium between surface emissions and the high-grade air.
- g. At the end of the 2-hour purge time, connect a clean sorbent tube to the exit tubing on the Teflon™ box and the SKC pump. Start the pump and run it for 6 minutes. This results in a 300-cm<sup>3</sup> volume of air being passed through the sorbent sampling tube.
- h. The sorbent tube is removed from the sampling line, capped, and returned to its storage tube. Sample tube number, sampling location, date, time, and any observations are recorded in the notebook.
- i. Reposition the Teflon™ box at the next sampling location, and repeat the purge/sampling procedure.
- j. In addition to the three surface emission samples, collect a duplicate emission sample from one location, a sample of the high-grade cylinder air, an ambient air sample, and a "trip blank," where no sample is loaded onto a conditioned tube. These extra samples were used as quality control samples.

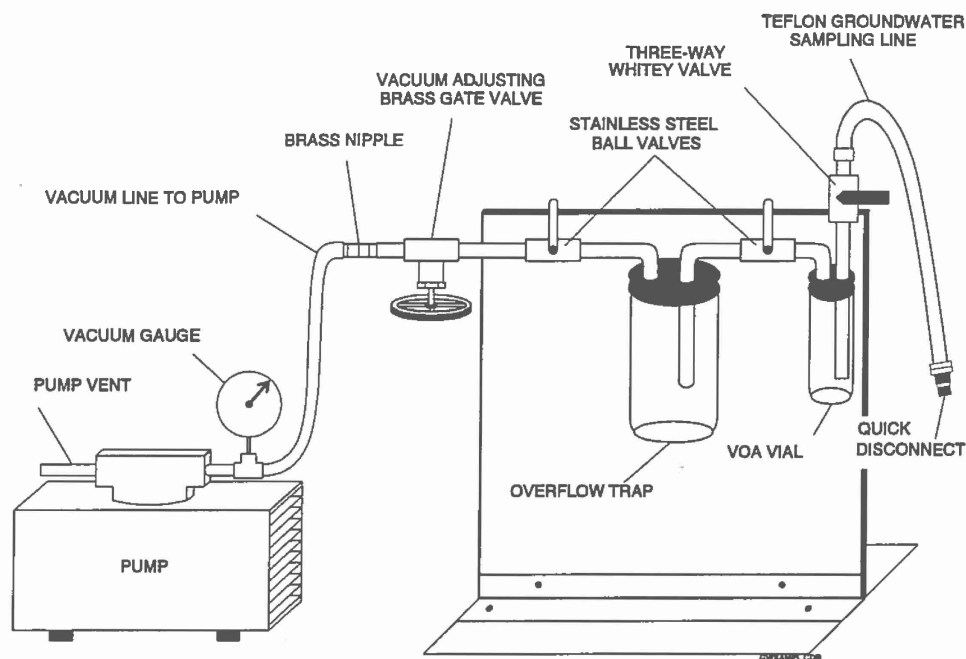
Surface emission sampling was performed in June and August 1994 and January 1995, in conjunction with the in situ respiration tests conducted at these times.

## **5. Groundwater Sampling**

Groundwater samples were collected and analyzed from both the saturated zone of the soil profile at the study site and the upper and lower screened intervals of the two in-well air stripping systems. Groundwater contamination was tracked to indicate the organic removal efficiencies of the stripping wells, the delivery of organics from the saturated to the vadose zone, and the overall groundwater remediation at the test site.

Samples were collected from 6, 9, 12, and 15 feet bgs at the eight monitoring points using a pump-assisted sampling system, developed by Battelle Columbus Laboratories, which permitted the controlled withdrawal of groundwater from the saturated zone. Groundwater samples were preserved and shipped at 4°C to Battelle for analysis.

Samples were collected using the vacuum-assisted sampling system shown in Figure 11. The system was designed so that the groundwater samples were pulled through a volatile organic analysis (VOA) vial and the sample was collected from a portion of a continuous water column. Sampling from within the continuous water column allowed for headspace-free sample removal and minimized the loss of volatiles. The VOA vial was used to collect, store, and ship the groundwater sample. These 40-mL vials were purchased in a certified clean state from I CHEM Research (Product No. G236-0040).



**Figure 11. Schematic of the Apparatus Used to Collect Groundwater Samples.**

The sampling procedure involved the following steps:

- a. Attach an overflow trap and the VOA vial to the sampling system. Connect the pump's vacuum port via tubing to the brass nipple on the sampling manifold.
- b. Upstream of the VOA vial, place a Teflon™ sample line into a beaker of clean water.

- c. Confirm that the overflow trap and VOA vial have been tightened in place.
- d. Close the brass gate valve and open the two ball valves. Turn the handle on the three-way Whitey valve so that the arrow points down.
- e. When the pump is turned on, the brass gate valve slowly opens until the water from the beaker gently flows through the sampling line, through the VOA vial, and into the overflow trap. The packing nut on the brass valve is tightened to maintain this desired flow rate.
- f. After setting this flow rate, simultaneously the right ball valve is closed and the Whitey valve is turned so that the handle's arrow points up. This allows the water in the Teflon™ sampling line to drain back into the beaker. Closing the left ball valve isolates the sampling manifold from the pump.
- g. Remove the quick-connect sampling line from the beaker of water and turn the Whitey valve so that the arrow points down. This relieves any slight vacuum on the VOA vial. Unscrewing the VOA vial permits water in the Whitey valve to drain, resulting in the VOA vial being filled. This clean water is discarded, and the system is now ready for collecting groundwater samples.
- h. After draining the sampling system's trap and then reinstalling it, secure a clean VOA vial and connect the sampling line to a groundwater monitoring point via the quick-disconnect fitting. Start the pump and open the valves as previously described. Four to five VOA vial volumes of groundwater are pulled through the VOA vial and into the sampling manifold's trap to ensure that the sample line is flushed and the vial contains a representative groundwater sample.
- i. Remove the VOA vial and add 3 drops of concentrated sulfuric acid to the water sample as a preservative. Cap the groundwater sample vial, label it, and store it in a cooler at 4°C. Record the sampling in the field notebook and complete the chain-of-custody form.
- j. Slowly open the right ball valve on the sampling system to relieve any vacuum on the overflow trap. Remove the trap and drain it. This extra water is placed in a 55-gallon for proper disposal.
- k. Re-assemble the system with a new VOA vial and connect it to the next monitoring point to repeat the procedure. Pull duplicate groundwater samples randomly from the monitoring points.

- l. Collect groundwater samples from the upper and lower screened intervals of the sparging wells, employing the same sampling technique for these samples.
- m. Clean the sampling system with distilled water during the sampling process if a carryover problem is anticipated. At the end of a sampling event, clean the system before storage. Use only distilled water to clean the system.
- n. Ship the groundwater samples in a cooler, with wet ice packs, via overnight delivery to Battelle. Samples are logged in upon receipt and stored at 4°C until analysis within the 14-day holding period.

Groundwater sampling was performed immediately prior to system startup in June 1994, and during each shutdown/respiration test prior to turning off the in-well air stripping system.

## **D. ANALYSIS**

### **1. Soil Analysis for JP-4**

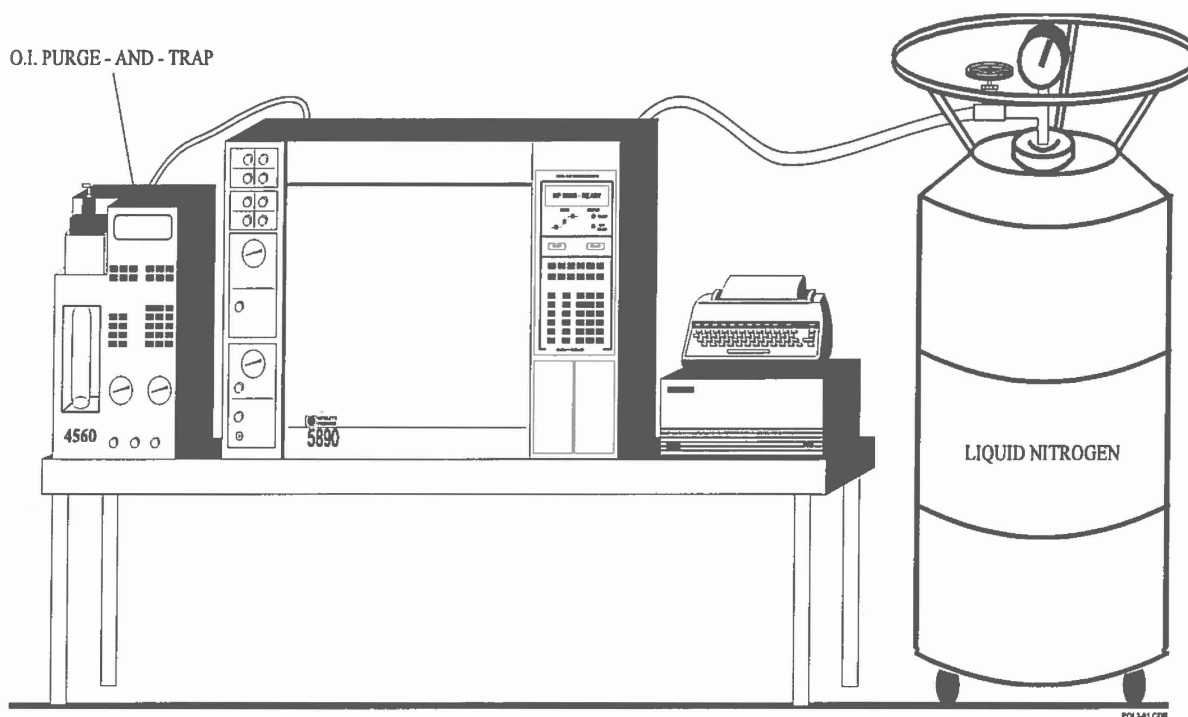
Soil samples were analyzed using a GC method employing a heated purge-and-trap technique. This method for processing soils contaminated with fuels has been shown to be comparable to extraction techniques while allowing for the identification of lower boiling compounds (Chang et al., 1992).

An O.I. Analytical Model 4560 Purge-and-Trap Concentrator was used in conjunction with a Hewlett-Packard Model 5890 Series II Gas Chromatograph (Figure 12) to analyze for the 19 specific hydrocarbon compounds listed in Table 3 that are commonly associated with JP-4. The chromatography of these compounds resulted in a JP-4 "fingerprint" that was used to track the fate of the different hydrocarbon components and boiling point fractions of the aged JP-4 contamination. A 19-component calibration mixture was prepared to confirm the performance of the analytical system for the expected organics and to permit qualitative and quantitative analyses of the groundwater samples.

The purge-and-trap was operated with a sorbent trap that contained Tenax TA and activated charcoal (Supelco Catalog No. 2-4933). This combination of sorbent materials was well suited to capture JP-4 type organic compounds while having a low affinity for water. The following purge-and-trap conditions were used in the analysis:

- Trap purge temperature = 25°C
- Sample purge time = 9 minutes
- Trap dry purge time = 8 minutes
- Trap desorption temperature = 180°C
- Trap desorption time = 5 minutes

- Trap bake temperature = 190°C
- Trap bake time = 10 minutes
- Sample valve and transfer line temperatures = 100°C
- Groundwater sample temperature during purge = 85°C
- Sample inlet temperature = 100°C
- Purge gas = ultra-high-purity helium
- Purge gas flow = 40 mL/min.



**Figure 12. Schematic of the Analytical Instrumentation Used for Purge-and-Trap Analyses of Soil and Groundwater Samples Collected During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.**



**TABLE 3. SPECIFIC HYDROCARBON COMPOUNDS COMMONLY ASSOCIATED WITH JP-4**

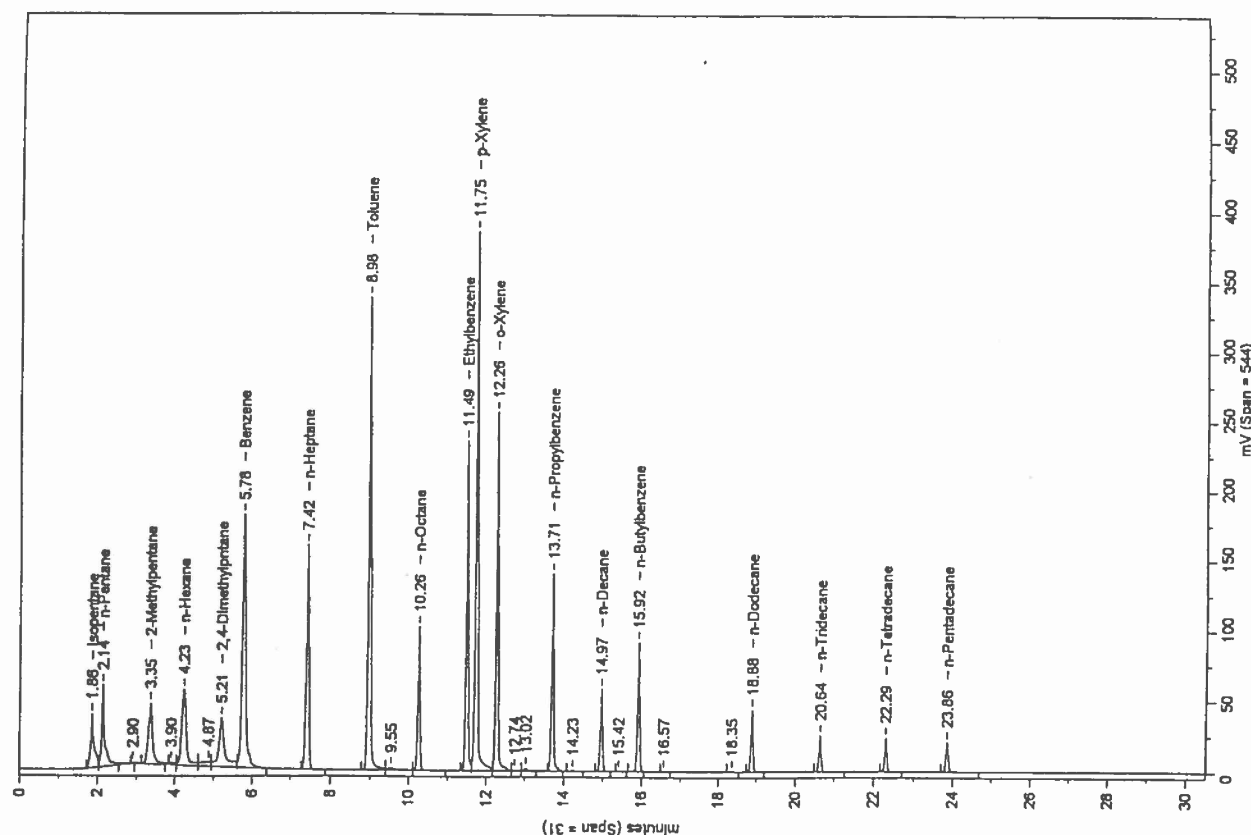
isopentane	benzene	<i>p</i> -xylene	<i>n</i> -dodecane
<i>n</i> -pentane	<i>n</i> -heptane	<i>o</i> -xylene	<i>n</i> -tridecane
2-methylpentane	toluene	<i>n</i> -propylbenzene	<i>n</i> -tetradecane
<i>n</i> -hexane	<i>n</i> -octane	<i>n</i> -decane	<i>n</i> -pentadecane
2,4-dimethylpentane	ethylbenzene	<i>n</i> -butylbenzene	

The O.I. Analytical Model 4560 Purge-and-Trap Concentrator was equipped with an optional infra-spargue heater that permitted heating the groundwater sample to 85°C while purging organics from the sample. This feature made it possible to analyze for both volatile and semivolatile organics. The dry purge function was employed to reduce the moisture delivered from the sorbent trap to the GC during desorption.

A Hewlett-Packard 5890 Series II GC was configured with a wide-bore HP-1 capillary column (30-meter × 0.53-mm × 2.65-μm film thickness) and a flame ionization detector (FID). The analytical conditions for the GC included a temperature program that started at 25°C with a 4-minute initial hold time. The GC oven temperature was then ramped at 8°C/min to a final temperature of 225°C with a final hold time of 1 minute. The initial temperature was held slightly below room temperature through the controlled release of liquid nitrogen to the oven. This slightly reduced temperature enhanced compound resolution without causing column plugging due to freezing of residual moisture from the purge-and-trap concentrator.

The 19-component qualitative/quantitative calibration mixture for the JP-4 "fingerprint" analysis was prepared from a 16-component ASTM D3710 Quantitative Calibration Mixture (Supelco, Inc., Catalog No. 4-8879) and separate stocks of benzene, ethylbenzene, and *o*-xylene. Working calibration stocks were prepared using sequential dilutions in methanol, and the resulting mixtures were used to establish chromatographic retention times, compound-specific response factors, method detection limits, and optimized analytical conditions. A typical purge-and-trap/GC chromatogram of the calibration mixture is presented in Figure 13.

The analytical instrumentation was challenged with a multipoint calibration to establish method detection limits and linearity of response for the target compounds. The concentrations of each individual component in the mixture were not identical because of the nature of the purchased calibration solution. The low end of the calibration curve reflected concentrations of ~2 parts per billion (ppb) for each component. The upper end of the calibration curve was at ~400 ppb. The FID responded linearly over the calibration range. The analytical precision during the multipoint calibration activities also was acceptable, with



**Figure 13. A Typical Chromatogram for the 19-Component Calibration Mixture Analyzed Using the Purge-and-Trap Method.**

typical coefficient of variance values of less than 10 percent. All of the calibration work was based on processing 5-mL Millipore water (18 Mohm [MΩ] purity) samples spiked with the various methanol-based calibration mixtures.

The O.I. Analytical Model 4560 Purge-and-Trap Concentrator was configured for processing soil samples by changing the groundwater-fritted sparging vessel to a disposable test tube vessel and a needle sparger. The soil sample was loaded into the test tube and weighed. Generally, 1 to 2 grams of wet soil was analyzed. Millipore water (5 mL) was added to the soil sample and the test tube was installed in the purge-and-trap device with a Teflon™ compression fitting. The soil/water slurry was then processed by heating the purge vessel to 85°C with sparging for 9 minutes. Under these conditions, it was possible to duplicate the groundwater purging efficiencies while using the soil processing configuration.

Matrix recovery of the target compounds from a Tyndall soil sample was investigated by spiking soil with a methanol-based calibration mixture, then processing the sample using the purge-and-trap/GC protocol used for soil sample analyses. Recovery data presented in Table 4 indicated that the soil matrix is a more difficult medium than water to achieve quantitative recoveries. Extending the purge time beyond 9 minutes to enhance the

recovery efficiencies was not practical, as the extended purge times resulted in the transfer of excessive moisture to the sorbent trap and, eventually, to the GC column, which resulted in both chromatographic and FID stability problems. With recoveries generally above 75 percent for the target compounds, this method was comparable to EPA Method 3550 extraction recovery efficiencies for nonvolatile and semivolatile compounds.

**TABLE 4. SOIL RECOVERY DATA**

Compound	Matrix Spike Recovery (percent)	Compound	Matrix Spike Recovery (percent)
isopentane	70	<i>p</i> -xylene	83
<i>n</i> -pentane	108	<i>o</i> -xylene	91
2-methylpentane	81	<i>n</i> -propylbenzene	77
<i>n</i> -hexane	80	<i>n</i> -decane	52
2,4-dimethylpentane	75	<i>n</i> -butylbenzene	64
benzene	100	<i>n</i> -dodecane	64
<i>n</i> -heptane	73	<i>n</i> -tridecane	95
toluene	87	<i>n</i> -tetradecane	100
<i>n</i> -octane	70	<i>n</i> -pentadecane	65
ethylbenzene	84		

Soil data were reported on a dry-weight basis. Moisture levels in the soil samples were determined by weighing approximately 5 grams of wet soil, in triplicate, and drying the soil at 105°C for a 24-hour period. The dry soil was removed from the drying oven, allowed to cool to room temperature in a desiccator, and reweighed. The change in soil mass reflected the loss due to moisture. This percent soil moisture was used as a correction factor that permitted data to be reported on a dry-weight basis.

Duplicate analyses were performed on soil samples collected from two locations at the study site during the final sampling event. The coefficients of variance for TPH in soil samples collected at MP-2 and MP-8 at the 4-foot depth were 1.6 percent and 9.5 percent, respectively, with a median variance of 5.6 percent.

Data generated from the samples collected at the start and termination of the demonstration included compound-specific concentrations, reported in µg/g dry weight, and boiling point range distributions and TPH values, reported in µg/g as hexane equivalents.

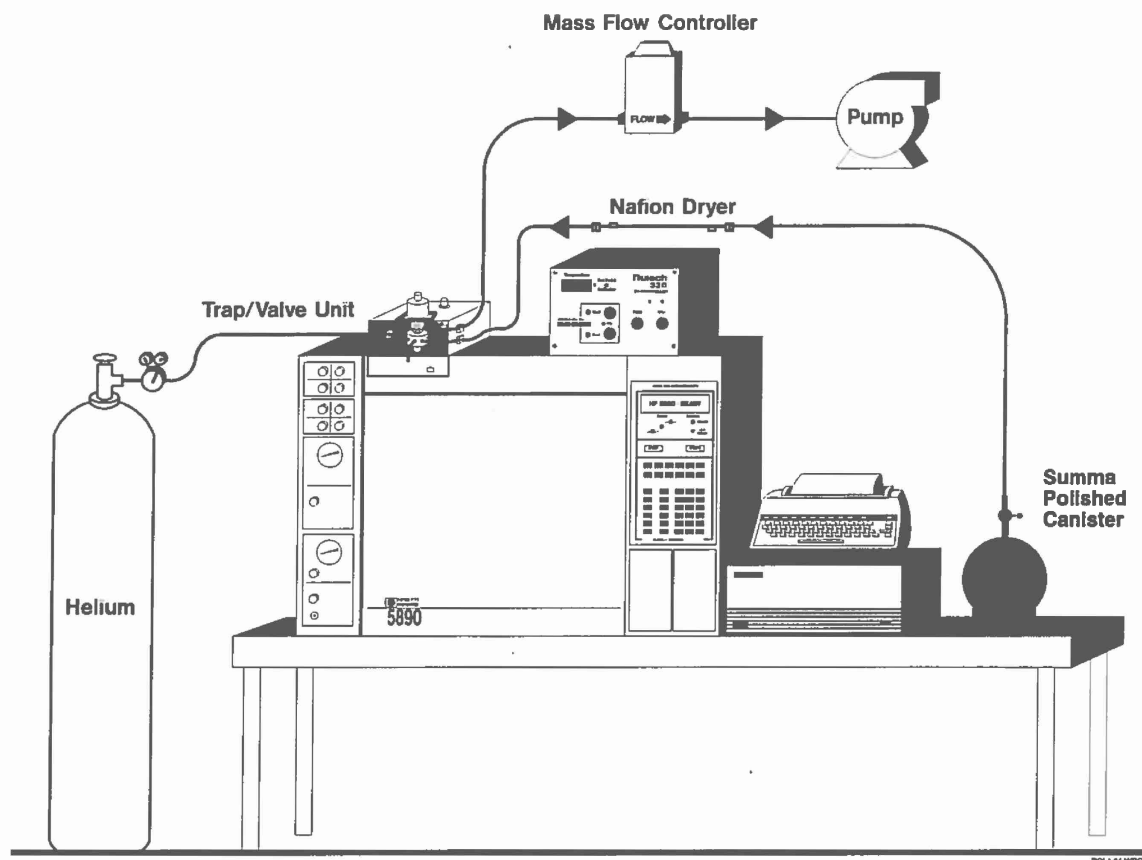
## 2. Soil Gas Analysis for JP-4

The sorbent tubes used to collect soil gas samples were shipped to Battelle for analysis of JP-4 and TPH by boiling point split using GC. A calibration mixture containing the 19 compounds of interest listed in Table 3 was processed to establish retention times and response factors to qualify and quantify the targeted compounds.

The organic compounds retained by the sorbent materials in the sampling tubes were thermally desorbed into an evacuated 1-liter Summa polished air sampling canister to avoid overwhelming the detector with excessively high hydrocarbon loadings. A Dynatherm, Model 10 sorbent tube conditioner/desorber was used to heat the sorbent tube during delivery of the soil gas organics to the evacuated canisters. The desorption temperature was 250°C, and the helium purge gas flow rate was 20 cm<sup>3</sup>/minute. The tubes were desorbed for 15 minutes, resulting in a 300-cm<sup>3</sup> helium flush volume. Following desorption into the canister, the canister pressures were brought to 1 atmosphere. This resulted in diluting the original 50-cm<sup>3</sup> soil gas sample to a volume of 2 liters. Quantitative results from the analysis of each sorbent tube were corrected for this dilution associated with desorbing the sample into the canister.

The instrumentation and analytical technique used to process the sorbent tubes was based on U.S. Environmental Protection Agency (EPA) Method TO-14, which is employed to identify toxic organics in ambient air (EPA, 1988). The analysis involved collecting the VOCs from a gas sample on a cryogenically cooled glass bead trap, then desorbing the trapped organics by ballistically heating the cold trap and delivering the organics to a GC for qualitative/quantitative analyses. The primary modification to the TO-14 method was the use of sorbent tubes to collect the soil gas organic compounds as opposed to collecting whole air samples in evacuated air sampling canisters.

The automated GC system (Figure 14) consisted of a Hewlett-Packard Model 5890 gas chromatograph with a flame ionization (FID) detector. A Hewlett-Packard 3396A integrator, in conjunction with an HP Model 9122 disk drive, received detector output signals and stored data. The disk drive also provided access to the computer program used to automate both sample refocusing from the sorbent tube and the GC analysis. A modified NuTech Model 320 sample preconcentration unit was used to collect the organics from the canister. The unit contains two subsystems: (1) an electronic console that regulated various temperature zones, and (2) the sample-handling subassembly containing a six-port valve and cryogenic glass bead trap. The console controlled the temperatures of the valve body (120°C), the sample transfer lines (120°C), and the GC trap. The trap temperature was regulated by the controlled release of liquid nitrogen via a solenoid valve. The trap temperature during sample transfer from the sorbent tube was maintained at -150°C. The GC trap was then heated to 130°C to transfer the organics to the analytical column.



**Figure 14. Schematic of the Analytical Instrumentation Used for Analyses of the Soil Gas Samples Collected on Sorbent Tubes During the In-Well Air Stripping/Bioventing Study.**

Sample flow from the sorbent tube to the GC trap was controlled using (1) a Tylan™ readout control unit, Model R032-B; (2) a Tylan™ 0 to 100 standard cm<sup>3</sup>/min mass flow controller, Model MFC-260; (3) a Thomas™ dual-diaphragm pump; and (4) a Perma Pure™ dryer, Model MD-125-48F. The electronic flow controller made it possible to consistently desorb the organics trapped on the sorbent tube and deliver them to the GC refocusing trap. The Perma Pure™ dryer with a tubular hygroscopic ion-exchange membrane (Nafion™) was used to selectively remove any water vapor from the sorbent sample. The Nafion tube (30 cm × 0.1 cm ID) was embedded within a shell of Teflon™ tubing (0.25 cm ID). A countercurrent flow of dry zero air (300 cm<sup>3</sup>) was used to purge this shell and sweep

away the moisture that passed through the membrane. This type of dryer has been shown to have no affinity for both aromatic and straight-chained/branched petroleum hydrocarbons (Pliel et al., 1987).

A Dynatherm™, Model 10 sorbent tube conditioner/desorber was used to heat the sorbent tube during delivery of the soil gas organics to the canister system. A desorption temperature of 250°C with a helium purge gas flow of 20 cm<sup>3</sup>/minute was used during this desorption process. The desorption time for a sorbent tube was 15 minutes, resulting in a 300-cm<sup>3</sup> helium backflush volume.

The concentrations of the 19 target compounds listed in Table 3 were monitored in soil gas samples collected during this study. A high-pressure calibration cylinder was prepared at Battelle that contained these 19 organic compounds. In addition to these compounds, a TPH value, as hexane equivalents, was calculated.

The primary gas calibration mixture was prepared by making a "cocktail" of the target compounds in the same manner as used for preparation of the soil calibration mixture. This chilled mixture (1 mL) was injected into an evacuated 15.7-liter aluminum high-pressure cylinder and pressurized with nitrogen to 1,000 pounds per square inch gage (psig). The cylinder was fitted with a regulator and wrapped with electrical heating tape. The cylinder was heated to ~55°C to maintain all of the organics in the vapor phase. This "parent cylinder" contained the target compounds at parts per million by volume (ppmv) levels ranging from 1.2 to 17.8 ppmv. A gas-phase dynamic dilution system was used to generate working calibration standards. A method detection limit for the target compounds was determined to be 0.50 part per billion by volume (ppbv) when 300-cm<sup>3</sup> samples were processed.

Separations chemistry of the target compounds was accomplished using two 30-meter HP-1 capillary columns joined with a zero dead-volume butt connector. The internal diameter of the capillary was 0.53 mm with a 2.65-μm film thickness. An optimal chromatographic resolution was obtained by temperature-programming the GC oven from -50°C to 200°C at a rate of 8 degrees per minute following an initial temperature hold time of 4 minutes.

The FID area counts from the analysis of a sorbent tube were used to calculate the compound concentration at each sampling location. The sum of the FID area count was used to generate a TPH value, as hexane equivalent, by applying the hexane response factor to the total chromatogram FID area. Additionally, a TPH value, again as hexane, was calculated for various boiling point ranges. This was accomplished by summing the FID areas for regions of the chromatogram where the known molecular weight ranges eluted, and then multiplying by the hexane response factor.

The gas analysis GC was challenged with a multipoint calibration to establish method detection limits and linearity of response for the target compounds. The concentration of each individual component in the mixture was not identical because of the

nature of the purchased calibration solution. The low end of the calibration curve reflected concentrations of  $\sim 2$  ppbv for each component. The upper end of the calibration curve was at  $\sim 200$  ppbv. Values were forced through zero based on blank runs. The linearity of the response values for each component is presented in Table 5. Excellent linearity was shown for these compounds by the FID. A slight loss of linearity was observed for the high-molecular-weight compounds, as maintaining these semivolatile compounds in the vapor phase was difficult. Analytical precision for the calibration work on the triplicate samples also was acceptable, with typical coefficient of variance values of less than 10 percent. All of the calibration work was performed by collecting and analyzing 300-cm<sup>3</sup> gas samples.

**TABLE 5. SOIL GAS LINEARITY TABLE**

<b>Compound</b>	<b>Linearity of Response</b>	<b>Compound</b>	<b>Linearity of Response</b>
isopentane	0.99996	<i>p</i> -xylene	1.00000
<i>n</i> -pentane	1.00000	<i>o</i> -xylene	1.00000
2-methylpentane	1.00000	<i>n</i> -propylbenzene	0.99999
<i>n</i> -hexane	1.00000	<i>n</i> -decane	1.00000
2,4-dimethylpentane	1.00000	<i>n</i> -butylbenzene	1.00000
benzene	1.00000	<i>n</i> -dodecane	0.99551
<i>n</i> -heptane	1.00000	<i>n</i> -tridecane	0.99876
toluene	1.00000	<i>n</i> -tetradecane	0.97155
<i>n</i> -octane	1.00000	<i>n</i> -pentadecane	0.91472
ethylbenzene	1.00000		

Duplicate soil gas samples were collected during each sampling event. The average coefficient of variance for these 8 samples was 18.1 percent with a range of 1.3 percent to 43.1 percent.

### **3. Soil Gas Analysis for Oxygen, Carbon Dioxide, and TPH**

O<sub>2</sub>, CO<sub>2</sub>, and TPH concentrations were measured in the field in soil gas samples collected in Tedlar™ gas sampling bags. A GasTech™ O<sub>2</sub>/CO<sub>2</sub> meter (Model 3252OX) was used to measure O<sub>2</sub> and CO<sub>2</sub> and a TraceTector™ TPH analyzer was used to measure TPH concentrations. The meters were hooked in series to allow for complete analyses using the volume of gas in the Tedlar™ bag. Because the TPH meter contains a hot wire sensor that

alters the O<sub>2</sub> and CO<sub>2</sub> content in the gas stream, the meters were plumbed so that the gas sample passed through the GasTech™ meter before the TraceTector meter.

Before analysis of the samples, the meters were turned on and allowed to warm up. Once the meters stabilized, they were calibrated using appropriate gasses. The GasTech™ meter was calibrated using a gas mixture containing 10 percent O<sub>2</sub> and 4.99 percent CO<sub>2</sub>. The TraceTector™ TPH meter was calibrated against a 1,000-ppm hexane in air standard. All meters were zeroed against gasses free of the specific analyte.

When the oxygen concentration in any soil gas sample was below 10 percent, a 1:1 diluter was installed in the line between the two meters. The TPH values indicated on the meter were recorded, along with a note indicating that the diluter was used. All data generated using a diluter were corrected to actual TPH values.

#### 4. Surface Emission Analysis

The organic compounds retained by the sorbent materials in the sampling tubes were thermally desorbed, refocused, and analytically resolved via GC using the same instrumentation and analytical technique as for soil gas samples (see Section II.D.2). The 19-component calibration gas standard, described earlier, was processed to confirm the retention times and response factors for these compounds. Generally, the same sample volume collected during the surface emission sampling was used when processing the calibration gas. The organics collected on the sorbent tubes were directly desorbed to the GC and not into the canisters as described for the soil gas samples.

Compound concentrations were recorded on a parts per billion by volume (ppbv) basis, and these values were used to calculate emission rates of the compounds from the ground surface during operation of the well systems and when the systems were turned off. Surface emission flux rates of organic compounds from the soil surface into the atmosphere were calculated using a formula for dynamic enclosure techniques as follows:

$$F = CV_r/S \quad (\text{McVeety, 1993})$$

where:

F = flux in mass/area-time

C = the concentration of the gas in units of mass/volume

V<sub>r</sub> = volumetric flow rate of sweep gas

S = soil surface covered by enclosure.

This methodology for generating the surface emission flux values from the concentrations of the target compounds was applied to the sorbent sampling tubes collected at the Tyndall AFB study site.

Duplicate samples were collected from a total of seven locations during surface emission testing. The TPH coefficients of variance (CVs) for five of these samples ranged



*Sample Calculation:*

Benzene concentration at 12½ feet west of the well system on September 22, 1994 = 9.00 ppbv.

To generate the "C" value of mass/volume:

$$9.00 \text{ ppbv} = 0.00900 \text{ ppmv}$$

1 ppmv of benzene, with a molecular weight of 78, is = 0.00319 mg/L. Therefore, 0.00900 ppmv =  $0.00900 \times 0.00319 \text{ mg/L} = 0.0000287 \text{ mg/L}$ .

$$\text{"C"} = 0.0000287 \text{ mg/L.}$$

$V_r$  = The volumetric flowrate of the sweep gas, 2 L/minute.

S = The soil surface covered by the box was a constant 0.453 m<sup>2</sup>.

Therefore:

$$F = (0.0000287 \text{ mg/L} \times 2 \text{ L/minute})/0.453 \text{ m}^2,$$

$$F = 0.0000574 \text{ mg benzene}/0.453 \text{ m}^2/\text{minute},$$

$$F = 0.0574 \text{ } \mu\text{g benzene}/0.453 \text{ m}^2/\text{minute}.$$

from 1.16 to 14.1 percent with a median variance of 6.96 percent. The remaining two duplicate samples were extremely divergent with CVs of 84.9 and 96.6 percent. In these two cases, typically, low ppbv emission levels were detected in one of the sample pairs and an elevated concentration was observed for the duplicate. It is suspected that some extraneous contamination, not typically seen in the sorbent tubes, was introduced to the sorbent tube.

The average concentration of TPH measured in the trip blank sorbent tubes was 9.9 ppbv as hexane, and the cylinder air quality resulted in a mean TPH contribution to the emission measurements of 22 ppbv as hexane. No corrections to the surface emission data were made for trip blank or cylinder gas contributions, so the data presented reflect a worst case scenario.

Because of the low flux values associated with the surface emission measurements at system startup and during the first two shutdown tests, no surface emission samples were collected at the end of the demonstration.

## 5. Groundwater Analysis for JP-4

Organic contamination at the Tyndall AFB study site at POL-B was known to consist primarily of aged JP-4 jet fuel. The composition of this type of fuel is straight-chained and branched aliphatic compounds along with monoaromatic organics. Molecular weights range generally from pentanes to pentadecane for JP-4 fuel (Smith et al., 1981). Based on this information, the analysis of the groundwater samples involved methods development activities to accommodate this range of volatile to semivolatile compounds. The analytical method developed was based on U.S. EPA Method 5030 which addresses the use of a purge-and-trap technique, along with U.S. EPA Method 8015 which describes nonhalogenated volatile organic analyses by capillary GC.

The analytical technique for processing groundwater samples was the same as that used for soil samples except for the use of a fritted sparging vessel and a 7-minute purge time. Tyndall groundwater was matrix-spiked with the calibration mixture to determine percent recovery values (see Table 6). The recovery values were considered to be within acceptable limits ( $\pm 20$  percent) for all compounds except isopentane, tetradecane, and pentadecane. Isopentane eluted on the chromatogram where a methanol/water disturbance occurred, making integration of this compound difficult resulting in the elevated recovery data. The elevated recoveries for tetradecane and pentadecane were not unexpected, because the dissolved salts in Tyndall groundwater actually enhanced the purging efficiencies of these heavier-molecular-weight compounds.

During the sampling/analysis of the groundwater samples, duplicate samples were collected from the study site and processed to confirm the precision of both the sampling and the analytical techniques. Over this sample set, the CVs between duplicate analyses ranged from 4.4 to 1.1 percent with a mean value of 2.2 percent. This level of precision further validated both the sampling and the analytical techniques used during this study.

A series of blank water samples included a laboratory blank, a trip blank, and a trip blank to which the field stock of sulfuric acid preservative was added. Consistent results for these samples indicated that the shipping procedures and the addition of preservative to the samples, did not contribute significantly to any hydrocarbons being detected in the groundwater samples.

The results of the methods development activities confirmed that it was acceptable to utilize a heated purge-and-trap methodology on water samples and perform qualitative/quantitative analysis on the Tyndall AFB groundwater samples collected during the evaluation of the in-well air stripping devices.

Data generated from the samples collected during the demonstration included compound-specific concentrations for groundwater samples (reported in ppb), boiling point range distributions, and TPH. The boiling point ranges and TPH values were reported as hexane equivalents.

**TABLE 6. GC LINEARITY OF RESPONSES AND COMPOUND RECOVERIES FROM SPIKED GROUNDWATER SAMPLES**

Compound	Linearity of Response	Matrix Spike Recovery (percent)
isopentane	0.99990	151
<i>n</i> -pentane	0.99976	102
2-methylpentane	0.87711	106
<i>n</i> -hexane	0.99980	120
2,4-dimethylpentane	0.99998	110
benzene	1.00000	101
<i>n</i> -heptane	0.99963	115
toluene	1.00000	97
<i>n</i> -octane	0.99980	110
ethylbenzene	0.99993	99
<i>p</i> -xylene	0.99998	99
<i>o</i> -xylene	0.99993	106
<i>n</i> -propylbenzene	0.99998	101
<i>n</i> -decane	0.99796	102
<i>n</i> -butylbenzene	0.99990	102
<i>n</i> -dodecane	0.99900	110
<i>n</i> -tridecane	0.99998	106
<i>n</i> -tetradecane	0.99968	123
<i>n</i> -pentadecane	0.97660	149

## 6. Groundwater Analysis for Dissolved Oxygen

Dissolved oxygen (DO) was measured in groundwater samples to determine the effectiveness of the well systems for providing oxygen to support aerobic biodegradation in the aquifer. The analysis was conducted in the VOA vial immediately after it was removed from the water sampling device. An Orion™ DO meter (Model 821) was used to measure the O<sub>2</sub> concentrations. The meter was calibrated according to the manufacturer's directions using the provided calibration sleeve, and the electrolyte and membrane were replaced as needed. The data were recorded as mg-O<sub>2</sub>/L.

## 7. Groundwater Analysis for Conductivity

Conductivity was measured in groundwater samples in an attempt to follow the bromide tracer that was injected into the upper piezometers of the MBW well system. A Myron L Company pH/conductivity meter (Model 01489-04) was used to make field measurements of the conductivity of groundwater samples pulled from the probes at the 6-, 9-, 12-, and 15-foot depths. Approximately 10 mL of groundwater was transferred from the VOA vial into the meter chamber, and the meter was allowed to equilibrate before the readout was recorded.

### E. SYSTEM STARTUP

#### 1. Initial Samples

Initial soil gas and groundwater samples were collected on 4 June 1994, prior to turning on the system. Soil gas samples were analyzed in the field for O<sub>2</sub>, CO<sub>2</sub>, and TPH concentrations. Groundwater samples were analyzed in the field to determine the level of dissolved oxygen.

The data from the initial set of soil gas samples are presented in Table 7. The data show that the oxygen concentration was below ambient (20.9%) at all points except MP-5. The oxygen at this location was near ambient and the TPH levels were very low compared to the rest of the locations. In general, the soils on the southern side of the well

TABLE 7. INITIAL SOIL GAS SAMPLE DATA

Monitoring Point	2 Feet bgs			4 Feet bgs		
	O <sub>2</sub> (percent)	CO <sub>2</sub> (percent)	TPH (ppm)	O <sub>2</sub> (percent)	CO <sub>2</sub> (percent)	TPH (ppm)
MP-1	15.0	3.9	1,900	14	4.5	5,400
MP-2	12.9	5.5	900	6.0	10.0	3,200
MP-3	9.0	9.0	3,200	NA	NA	NA
MP-4	8.2	7.2	7,000	NA	NA	NA
MP-5	20.0	0.7	46	19.5	2.2	105
MP-6	0.6	15.1	1,500	NA	NA	NA
MP-7	4.2	11.8	1,100	0.8	15	3,300
MP-8	2.1	14.8	540	2.1	15.6	640

NA - Data not available due to presence of water in monitoring probe.

systems were lower in  $O_2$ . The data showed an inverse correlation between  $O_2$  and  $CO_2$  concentrations, an indication that the depressed  $O_2$  was due to biological activity. There was no definite correlation between TPH concentration and oxygen levels. The oxygen concentrations were not as low as they were during the initial site characterization, suggesting that the conditions in the soil had not had sufficient time to overcome the upset of the installation process.

## 2. Modified KGB System

The modified KGB system was installed in an 8-inch-diameter case. The system was positioned so that a rubber packer was placed above the top of the upper screen to direct vapor into the vadose zone and prevent atmospheric release. The system was started on 4 June 1994, and an experiment was conducted to examine the air flow rate and head development characteristics of the well system. Due to the shallow vadose zone, it was necessary to determine the maximum air flow rate that could be used without discharging TPH vapor to the atmosphere through the soil surface. The air flow rate was varied from 0 to 2.0 cfm. The head was determined by measuring the depth of the water in the piezometers installed in conjunction with the upper and lower screen sections of the well casing. The results from the flow rate experiment are shown in Figure 15. The data showed that the head remained at background levels regardless of the air flow rate. This indicated that the well system was not moving water. Upon further examination, it was discovered

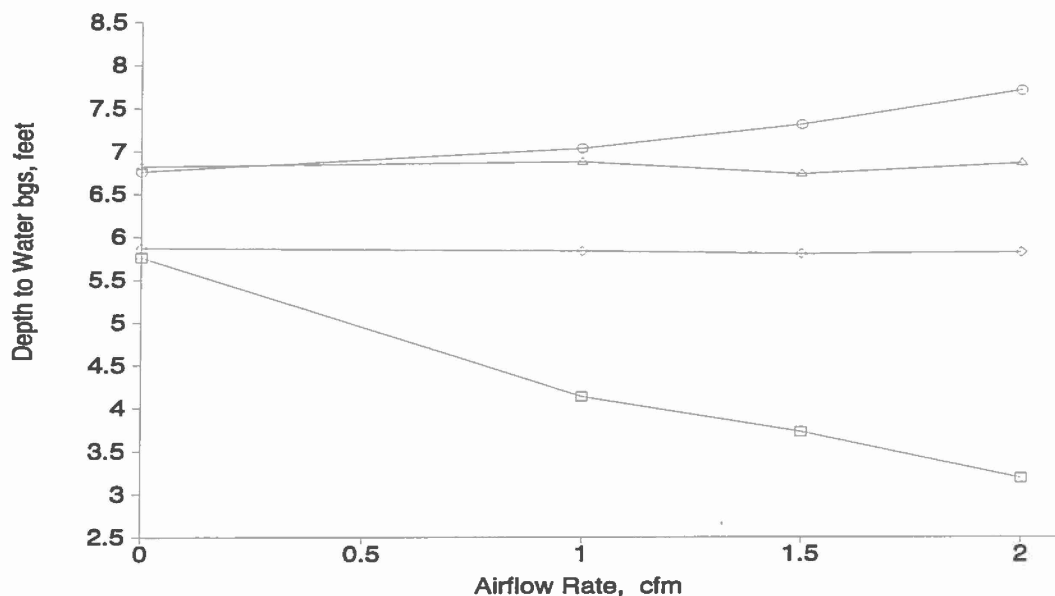


Figure 15. Water Depths in Piezometers as a Function of Air Flow Rate.  
 △ and ◇ mKGB System; ○ and □ MBW System.

that the air distributor was separated from the air line and that the air lift action was prevented due to a coarse "burping" effect. Repairs were scheduled and the MBW system was started, as described in Section II.E.3.

### **3. Modified Bioventing System**

The in-well air stripping system installed in the modified bioventing air injection well was started on 4 June 1994. An experiment was conducted varying the air flow rate between 0 and 2.5 cfm to monitor head and to determine the maximum rate at which air could be injected without releasing TPH vapor through the soil surface.

The head was measured as the difference in water level in the piezometers associated with the upper and lower screens of the well casing. The developed head is plotted against the air flow rate in Figure 15. The data showed a 1-foot head difference between the upper and lower screens with the system off. With the system running, the head developed across the well as a function of air flow rate. The trend in the data indicates that the maximum achievable head was not achieved at the flow rate of 2.0 cfm.

Although it may have been desirable to operate the well system at a higher air flow rate to increase water movement through the well, vapor release became apparent when the air flow rate was at 1.5 cfm, while no vapors were observed at 1.0 cfm. Based on this observation, the air flow rate was set at 1.0 cfm. At this air flow rate, there was a head difference of approximately 2.9 feet between the upper and lower screens; an increase of 1.9 feet was attributed to the air lift pumping. The system was turned off and allowed to come to equilibrium. The water levels in the piezometers returned to properitoneal levels after approximately 24 hours.

The system was started and the study was initiated on 6 June 1994. The air flow rate was set at 1.0 cfm resulting in a system pressure of 20 psig. The system was operated for 2 hours and the water levels were measured in the piezometers. The water levels at the upper and lower screens were 5.0 and 7.01 feet bgs, respectively. Although the water levels measured after startup were different from the levels measured during the head experiment, the system did develop the same head difference of approximately 2 feet.

A bromide tracer study was initiated on June 6, 1994, when it was determined that the system was operating properly. A slug of a 5,000 ppm NaBr solution was injected into the four shallow piezometers and conductivity measurements were made on groundwater samples collected from the 32 groundwater monitoring probes and the upper and lower water sampling probes associated with the well system. The conductivity data were used to monitor groundwater movement within the systems radius of influence.

The MBW system was operated for approximately 1 month when it was noticed that the air distribution frit was becoming clogged and the head that had developed across the well was diminishing. The air compressor was turned off and the system was removed from the well. The frit was removed, cleaned, and modified by drilling a gradient distribution of

holes into the sides of the porous section. The frit was reinstalled and the system returned to operation. Head measurements indicated that the system was performing as it was at the initial startup.

After approximately 10 days of operation, a pressure-relief valve on the compressor failed, causing the compressor to remain on and not cycle. The system was temporarily turned off, the valve was replaced, and the system was returned to operation. The system was run without interruption for the remainder of the 3 months.

#### 4. System Equilibration

Soil gas samples were collected on a nominal weekly basis and analyzed for O<sub>2</sub>, CO<sub>2</sub>, and TPH concentrations. The data indicated that the bioventing component of the system came to equilibrium with regard to oxygen [by 16 June 1994], but the TPH concentrations continued to decrease through 7 July 1994. The data from the analyses of the soil gas extracted on 16 June 1994, are presented in Table 8. The data show that the MBW system was able to oxygenate the total volume of soil and that the oxygen concentrations were greater than 16.0 percent at all locations. The analytical data from the samples collected on 7 July 1994 are presented in Table 9. The data show that the oxygen concentrations remained near the values observed on 16 June 1994, while the TPH concentrations were significantly lower. Data from sample analyses conducted after 7 July 1994, showed that the TPH levels remained at the lower levels shown in Table 9.

**TABLE 8. SOIL GAS SAMPLE DATA FROM 16 JUNE 1994**

Monitoring Point	2 Feet bgs			4 Feet bgs		
	O <sub>2</sub> (percent)	CO <sub>2</sub> (percent)	TPH (ppm)	O <sub>2</sub> (percent)	CO <sub>2</sub> (percent)	TPH (ppm)
MP-4	18.2	1.5	420	18.2	1.4	1,900
MP-2	17.0	2.5	500	17.2	2.3	1,640
MP-3	18.0	1.5	2,000	NA	NA	NA
MP-4	19.5	0.3	1,800	20.0	0	0
MP-5	18.2	0.5	0	19.0	0.6	0
MP-6	17.0	2.0	1,280	19.8	0.6	0
MP-7	17.0	2.0	88	17.0	2.1	1,100
MP-8	17.0	2.1	116	17.5	1.7	176

NA - Data not available due to probe clogging.

**TABLE 9. SOIL GAS SAMPLE DATA FROM 7 JULY 1994**

Monitoring Point	2 Feet bgs			4 Feet bgs		
	O <sub>2</sub> (percent)	CO <sub>2</sub> (percent)	TPH (ppm)	O <sub>2</sub> (percent)	CO <sub>2</sub> (percent)	TPH (ppm)
MP-1	19.9	0.6	33	20.5	0.0	16
MP-2	20.0	0.3	120	20.3	0.0	20
MP-3	20.0	0.0	300	20.2	0.0	20
MP-4	NA	NA	NA	20.0	0	9
MP-5	19.5	0.6	19	20.2	0.0	0
MP-6	20.2	0.0	0	20.1	0.0	0
MP-7	20.0	0.3	0	20.3	0.0	3
MP-8	20.0	0.0	3	20.0	0.0	4

NA - Data not available due to presence of water.

## **F. SHUTDOWN/RESPIRATION TESTS AND SYSTEM MONITORING**

### **1. Shutdown/Respiration Test 1**

The first respiration test was conducted in October 1994, after the system had been operating for 3 months. Surface emission measurements were made (see Section II.C.4); groundwater and soil gas samples were collected and sent to Battelle for analysis (see Sections II.C.5 and II.C.3); measurements of initial oxygen, carbon dioxide, and TPH in soil gas were made (see Sections II.C.2 and II.D.3); and groundwater samples were extracted and analyzed for DO concentrations (see Section II.D.6) before the compressor system was shut off. The depth to groundwater was measured in the five piezometers associated with the MBW and modified KGB well systems, and the temperature readings from the subsurface thermocouples were recorded. System temperature, flow rate, and pressure were recorded.

After all of the activities described above were completed, the air compressor running the MBW system was shut off and respiration monitoring began. The monitoring entailed collecting a series of soil gas samples from each soil gas probe over a 5-day period and measuring concentrations of oxygen, carbon dioxide, and TPH in the field using portable field meters. The soil gas samples were extracted using the initial method described in



Section II.C.2. The values for each parameter were recorded on data log sheets along with the date, time, meter ID, and name of person recording the data.

During the shutdown period, it was observed that the O<sub>2</sub> and CO<sub>2</sub> concentrations changed very slowly. Because of the perceived slow respiration rate, the test was extended and respiration measurements continued for a second week. After 14 days, the test was concluded. The air distributor at the bottom of the mKGB system was replaced and the air compressor line was switched to the modified KGB well system and turned on. The air flow rate was set at 1 cfm and depth to groundwater measurements were recorded for the five piezometers associated with each well system.

## **2. Shutdown/Respiration Test 2**

The second shutdown/respiration test was conducted over a 2-week period in January 1995. Groundwater, soil gas, and surface emission samples were collected for laboratory analyses (see Section II.C) prior to turning the modified KGB system off. Initial groundwater samples were then extracted and analyzed in the field for DO, and initial soil gas samples were extracted using the modified sampling procedure described in Section II.C.2 and analyzed in the field for O<sub>2</sub>, CO<sub>2</sub>, and TPH. Temperature readings all of the thermocouples and depth to groundwater in all of the piezometers were measured and recorded. The system was then turned off and respiration monitoring began.

## **3. Shutdown/Respiration Test 3**

The third and final shutdown/respiration test was conducted in June 1995, after 9 months of operation of the modified KGB system. Soil gas and groundwater samples were collected before shutting down the system (see Section II.C) and sent to Battelle for JP-4 analysis (see Section II.D). Soil gas and groundwater samples were then collected and analyzed for O<sub>2</sub>, CO<sub>2</sub>, TPH, and DO concentrations, respectively. Soil gas samples were extracted using the device shown in Figure 8. Groundwater samples were collected according to the method described in Section II.C.5. Temperature readings all of the thermocouples and depth to groundwater in all of the piezometers were measured and recorded. The system was turned off, and respiration monitoring began by extracting a time series of soil gas samples and analyzing the samples for O<sub>2</sub>, CO<sub>2</sub>, and TPH.

## SECTION III RESULTS

### A. INITIAL SITE CHARACTERIZATION

#### 1. Soil JP-4 Concentrations

Initial soil samples were collected from 4, 8, and 12 feet bgs and the samples were analyzed for the 19 components that comprised the JP-4 fingerprint, for boiling point splits and for TPH. The analytical data from samples from the 4-, 8-, and 12-foot depths are presented in Tables 10, 11, and 12, respectively, where data below the detection limit are indicated by BDL. The data show that the hydrocarbon contamination levels were extremely variable over both the vertical and horizontal extent.

The data contained in Table 10 indicate that the 4-foot depth was the more contaminated among the three depths. The concentrations of BTEX constituents in each sample were totaled, and the resulting BTEX and TPH concentrations were averaged over the eight MPs. The average BTEX and TPH concentrations were calculated to be 48.3 and 618 mg/kg, respectively. Soils collected from MP-1 did not show significant contamination, with the concentration of all 19 compounds and TPH being below the detection limit. MP-6 and MP-8 at 4 feet also were significantly less contaminated than the other points, with only trace levels of 11 and 13 of the 19 compounds being detected, respectively, and TPH concentrations of 1.01 and 3.25 mg/kg, respectively. MP-2 was significantly more contaminated than the other locations, with a TPH concentration of more than 2,000 mg/kg; however, benzene was not detected in this sample. The majority of the contamination at the 4-foot depth fell in the molecular weight range between C7 through C12, a composition consistent with aged JP-4.

Table 11 contains the analytical results from the soil samples collected from the 8-foot depth. The data show that the contaminant concentrations were significantly lower than at the 4-foot depth, with averaged BTEX and TPH concentrations of 1.75 and 32.1 mg/kg, respectively. MP-2 was the most contaminated location, having BTEX and TPH concentrations higher than 9 and 200 mg/kg, respectively. These concentrations were significantly higher than at the other locations where BTEX and TPH concentrations ranged between 0.2 and 3.19 mg/kg and 2 and 15 mg/kg, respectively. There was no clear distribution within the molecular weight ranges as observed at the 4-foot depth.

Soils collected from the 12-foot depth were the least contaminated with averaged BTEX and TPH concentrations of 1.11 and 11.7 mg/kg, respectively (Table 12). MP-3 and MP-4 had TPH concentrations over 37 mg/kg, significantly higher than the remaining six locations which had TPH values between 1.44 and 5.53 mg/kg. BTEX concentrations ranged from 0.24 to 2.87 mg/kg at MP-1 and MP-2, respectively. The majority of the hydrocarbons at MP-3 and MP-4 fell in the range of C6 to C13. As with the soils from the

**TABLE 10. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (mg/kg) FOR INITIAL SOIL SAMPLES COLLECTED FROM 4 FEET bgs DURING INSTALLATION**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	1.85	BDL	BDL	BDL	BDL	0.04	BDL
<i>n</i> -pentane	BDL	5.16	0.88	0.64	BDL	0.08	0.25	BDL
2-methylpentane	BDL	6.83	1.00	BDL	0.12	BDL	2.72	BDL
<i>n</i> -hexane	BDL	3.15	0.35	0.28	0.25	0.01	2.10	0.02
2,4-dimethylpentane	BDL	9.57	2.24	1.20	0.43	BDL	6.07	BDL
benzene	BDL	BDL	3.29	2.60	BDL	BDL	9.83	0.04
<i>n</i> -heptane	BDL	42.72	3.20	0.91	1.15	BDL	9.57	0.01
toluene	BDL	35.64	19.62	3.18	0.74	0.02	17.26	0.02
<i>n</i> -octane	BDL	13.36	3.00	6.90	13.33	BDL	25.77	BDL
ethylbenzene	BDL	16.02	3.15	5.42	21.91	BDL	5.00	0.02
<i>p</i> -xylene	BDL	83.66	20.49	9.12	11.50	0.01	20.07	0.09
<i>o</i> -xylene	BDL	52.03	15.68	2.78	14.23	0.01	18.25	0.03
<i>n</i> -propylbenzene	BDL	17.37	4.11	10.07	18.33	0.01	25.51	BDL
<i>n</i> -decane	BDL	11.9	8.60	13.47	24.67	0.01	17.27	0.03
<i>n</i> -butylbenzene	BDL	18.54	6.49	10.16	7.20	0.02	1.60	0.04
<i>n</i> -dodecane	BDL	13.96	6.38	3.23	BDL	BDL	BDL	0.09
<i>n</i> -tridecane	BDL	0.35	0.13	1.99	BDL	0.03	0.06	0.05
<i>n</i> -tetradecane	BDL	BDL	0.14	BDL	0.03	0.03	1.05	0.06
<i>n</i> -pentadecane	BDL	BDL	0.26	0.08	0.04	0.03	2.95	0.03
<b>Molecular Weight Ranges</b>								
< C5	BDL	0.52	BDL	BDL	0.03	BDL	BDL	0.10
C5	BDL	11.43	0.91	0.66	0.31	0.08	0.46	0.61
C6	BDL	52.9	16.02	9.74	1.62	0.01	45.14	0.16
C7	BDL	292.94	115.80	45.50	12.30	0.04	130.98	0.06
C8	BDL	558.61	165.61	123.33	142.00	0.06	232.71	0.18
C9	BDL	433.07	116.66	129.05	294.15	0.06	296.18	0.14
C10	BDL	206.41	64.70	91.58	121.72	0.14	52.54	0.36
C11	BDL	328.59	125.98	130.20	22.31	0.12	0.72	0.21
C12	BDL	227.84	86.63	122.31	0.16	0.06	BDL	0.45
C13	BDL	1.61	1.15	11.13	BDL	0.08	0.06	0.45
C14	BDL	BDL	0.45	BDL	0.14	0.19	11.44	0.33
C15	BDL	BDL	2.12	0.53	0.48	0.17	45.54	0.08
> C15	BDL	BDL	2.88	1.35	0.51	BDL	41.00	0.12
TPH	< 1	2,113.92	708.91	665.38	595.73	1.01	856.77	3.25

BDL - Below detection limit.

**TABLE 11. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (mg/kg) FOR INITIAL SOIL SAMPLES COLLECTED FROM 4 FEET bgs DURING INSTALLATION**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.02	4.27	0.39	0.10	BDL	BDL	0.08	BDL
<i>n</i> -pentane	0.03	BDL	0.15	BDL	BDL	BDL	BDL	BDL
2-methylpentane	0.03	0.12	0.31	BDL	BDL	0.13	BDL	BDL
<i>n</i> -hexane	0.02	0.16	0.20	0.01	0.01	0.04	BDL	0.25
2,4-dimethylpentane	0.03	0.35	0.51	BDL	0.01	BDL	0.03	BDL
benzene	0.12	BDL	0.08	0.02	BDL	0.17	0.07	BDL
<i>n</i> -heptane	0.03	0.41	0.16	BDL	BDL	0.02	BDL	BDL
toluene	0.01	1.26	0.09	0.01	0.01	0.01	0.02	BDL
<i>n</i> -octane	0.01	0.55	0.06	BDL	0.01	BDL	BDL	BDL
ethylbenzene	0.03	0.83	0.42	0.01	0.06	0.03	0.02	0.01
<i>p</i> -xylene	0.12	4.91	1.77	0.04	0.02	0.10	0.10	BDL
<i>o</i> -xylene	0.05	2.65	0.83	0.02	0.03	0.03	0.05	0.01
<i>n</i> -propylbenzene	0.01	0.86	0.04	BDL	0.04	0.01	0.02	0.01
<i>n</i> -decane	0.01	1.20	0.05	BDL	0.16	0.01	0.17	0.02
<i>n</i> -butylbenzene	0.02	0.72	0.05	BDL	0.22	0.02	0.16	0.02
<i>n</i> -dodecane	0.01	1.03	0.02	0.04	0.03	BDL	0.04	0.01
<i>n</i> -tridecane	0.06	11.34	0.52	0.50	0.40	0.03	0.07	0.03
<i>n</i> -tetradecane	0.06	6.93	BDL	0.08	0.06	0.04	0.01	0.06
<i>n</i> -pentadecane	0.01	1.40	0.03	0.01	0.03	0.04	0.01	0.07
<b>Molecular Weight Ranges</b>								
< C5	BDL	0.07	0.02	0.01	BDL	0.01	0.01	0.02
C5	0.05	3.11	0.44	0.07	0.12	0.20	0.06	BDL
C6	0.24	1.96	1.64	0.03	0.05	0.80	0.12	1.68
C7	0.21	8.57	2.23	0.02	0.04	0.19	0.07	0.06
C8	0.44	22.89	3.87	0.10	0.25	0.34	0.31	0.04
C9	0.25	21.49	1.64	0.09	0.63	0.16	0.44	0.12
C10	0.11	7.15	0.38	0.04	2.21	0.16	1.50	0.22
C11	0.10	14.11	0.53	0.05	2.49	0.12	1.25	0.15
C12	0.12	47.69	0.90	0.61	1.23	0.09	1.35	0.21
C13	0.16	36.61	1.55	1.29	1.26	0.09	0.58	0.19
C14	0.27	48.49	0.11	0.57	0.64	0.16	0.02	0.26
C15	0.12	2.22	0.53	0.01	0.09	0.13	0.02	0.18
> C15	BDL	1.71	0.75	0.08	0.29	0.10	0.12	0.07
TPH	2.07	216.07	14.59	2.97	9.30	2.55	5.85	3.20

BDL - Below detection limit.

**TABLE 12. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (mg/kg) FOR INITIAL SOIL SAMPLES COLLECTED FROM 12 FEET bgs DURING INSTALLATION**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	0.01	0.13	0.28	0.18	0.18	0.09	BDL
<i>n</i> -pentane	0.08	0.05	0.47	0.15	0.04	0.09	BDL	BDL
2-methylpentane	0.01	BDL	0.45	0.22	BDL	0.04	BDL	BDL
<i>n</i> -hexane	0.01	BDL	0.44	0.14	0.05	0.02	BDL	0.02
2,4-dimethylpentane	0.01	0.01	0.31	0.13	0.02	0.07	0.03	BDL
benzene	0.12	0.05	0.20	0.39	1.56	0.90	0.20	0.34
<i>n</i> -heptane	0.01	BDL	0.68	0.10	BDL	BDL	BDL	BDL
toluene	0.01	0.01	0.47	0.05	0.03	0.05	0.05	BDL
<i>n</i> -octane	0.01	0.01	0.81	0.03	BDL	BDL	BDL	BDL
ethylbenzene	0.06	0.02	0.18	0.15	0.01	0.11	0.01	0.27
<i>p</i> -xylene	0.03	0.12	1.24	0.46	0.04	0.32	0.05	BDL
<i>o</i> -xylene	0.02	0.06	0.78	0.26	0.02	0.16	0.03	0.07
<i>n</i> -propylbenzene	0.01	0.01	0.28	0.43	BDL	BDL	0.01	0.03
<i>n</i> -decane	0.06	0.01	0.50	0.38	0.02	BDL	0.05	0.01
<i>n</i> -butylbenzene	0.01	BDL	0.22	0.48	0.06	0.01	0.05	0.02
<i>n</i> -dodecane	0.04	BDL	0.05	0.77	0.06	BDL	0.02	0.02
<i>n</i> -tridecane	0.04	0.02	0.10	1.71	0.15	0.01	0.16	0.01
<i>n</i> -tetradecane	0.05	0.02	0.01	0.27	0.25	0.01	0.23	0.02
<i>n</i> -pentadecane	0.03	0.02	0.01	BDL	0.07	0.02	BDL	0.02
<b>Molecular Weight Ranges</b>								
< C5	BDL	0.01	0.02	0.03	0.07	0.04	0.10	0.01
C5	0.09	0.06	0.67	0.38	0.24	0.24	0.14	0.04
C6	0.17	0.07	2.69	1.41	1.44	1.07	0.22	0.60
C7	0.12	0.08	6.11	1.31	0.04	0.13	0.08	0.08
C8	0.35	0.39	9.65	2.01	0.20	0.69	0.14	0.43
C9	0.32	0.37	5.79	3.91	0.08	0.15	0.12	0.24
C10	0.21	0.06	2.57	5.09	0.43	0.10	0.42	0.21
C11	0.19	0.03	3.16	8.59	0.57	0.05	0.50	0.17
C12	0.13	0.09	3.82	10.80	0.51	0.01	0.89	0.16
C13	0.07	0.05	1.80	3.52	0.46	0.02	1.07	0.01
C14	0.23	0.07	0.01	0.48	1.27	0.03	1.20	0.10
C15	0.06	0.03	0.17	BDL	0.07	0.02	BDL	0.03
> C15	BDL	0.13	0.61	0.01	0.15	0.10	0.06	0.05
TPH	1.94	1.44	37.07	37.54	5.53	2.65	4.94	2.13

BDL - below detection limit.

8-foot depth, there was no clear distribution among the molecular weight ranges for the remaining locations.

The distribution of hydrocarbon contamination between the depths shows that most of the contaminant is at the 4-foot depth. Typically, groundwater at this site is at approximately 5 feet bgs, but it fluctuates significantly during heavy rainfalls such as those common in Florida. Because JP-4 tends to float on the top of the water table, significant smearing occurs during water-table fluctuation. The data shown in Tables 10, 11, and 12 indicate that significant smearing has occurred at this site. The contamination in the smear zone will be affected by the in-well air stripper when the water table is above the 4-foot depth and by bioventing when the water table level drops below the 4-foot depth.

## **2. Groundwater JP-4 Concentrations**

Groundwater samples were collected from four depths, 6, 9, 12, and 15 feet bgs, at each of the 8 monitoring points prior to operating the well system. The samples were analyzed for the 19 compounds comprising the JP-4 fingerprint, for molecular weight ranges based on the number of carbon atoms, and for TPH according to the methods in Section II.C. The results from these analyses are presented in Tables 13, 14, 15, and 16, where data below the detection limit are indicated by BDL.

BTEX and TPH concentrations in groundwater samples from 6 feet bgs ranged between 317 and 3,291  $\mu\text{g/L}$  and 959 and 8,604  $\mu\text{g/L}$ , respectively (Table 13). The concentrations of BTEX and TPH in groundwater extracted from 6 feet bgs averaged 1,172 and 4,898  $\mu\text{g/L}$ , respectively. Groundwater samples could not be extracted from MP-5 due to clogging problems, so this point was excluded from evaluation and is indicated as ND on the table. Groundwater from MP-3 and MP-4 were the most heavily contaminated with TPH having concentrations of 8,202 and 8,604  $\mu\text{g/L}$ , respectively. BTEX contamination was highest at MP-2 and MP-3 where concentrations were 2,196 and 3,291  $\mu\text{g/L}$ , respectively. MP-4 was the least contaminated point with BTEX and TPH having concentrations of 317 and 959  $\mu\text{g/L}$ , respectively. The distribution of hydrocarbon at the majority of points covered a molecular weight range from <C5 to C14.

Table 14 contains the results from analyses of groundwater from 9 feet bgs. The averaged BTEX and TPH concentrations in groundwater samples collected from this depth were 1,050 and 4,142  $\mu\text{g/L}$ , respectively, slightly lower than the concentrations at the 6-foot depth. The concentrations of BTEX and TPH ranged from 91 to 3,096  $\mu\text{g/L}$  and 526 to 7,668  $\mu\text{g/L}$ , respectively. MP-2 had both the highest BTEX and TPH concentrations. MP-5 had the lowest BTEX concentration and MP-4 had the lowest TPH concentration. As with the samples from the 6-foot depth, the hydrocarbons at the majority of the points covered a molecular weight range from <C5 through C14. Samples from MP-4 and MP-5 were the exceptions, having hydrocarbons in the C5 to C12 and C5 to C13 ranges, respectively.

Groundwater extracted from 12 feet bgs had averaged concentrations of 2,217 and 4,714  $\mu\text{g/L}$  for BTEX and TPH, respectively (Table 15). The concentrations throughout

**TABLE 13. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR INITIAL GROUNDWATER SAMPLES COLLECTED FROM 6 FEET bgs IN JUNE 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	118	149	61	BDL	ND	BDL	BDL	BDL
<i>n</i> -pentane	174	195	77	BDL	ND	BDL	BDL	BDL
2-methylpentane	74	100	55	BDL	ND	BDL	6	6
<i>n</i> -hexane	83	77	37	BDL	ND	10	BDL	BDL
2,4-dimethylpentane	296	280	197	13	ND	40	30	54
benzene	10	64	65	BDL	ND	27	7	171
<i>n</i> -heptane	33	46	31	BDL	ND	BDL	BDL	BDL
toluene	5	31	23	BDL	ND	19	10	30
<i>n</i> -octane	22	17	6	23	ND	31	BDL	5
ethylbenzene	74	226	351	72	ND	358	33	34
<i>p</i> -xylene	352	1,333	1,849	232	ND	428	244	115
<i>p</i> -xylene	89	542	1,003	13	ND	57	235	98
<i>n</i> -propylbenzene	55	34	20	15	ND	71	BDL	6
<i>n</i> -decane	17	15	24	5	ND	56	BDL	10
<i>n</i> -butylbenzene	43	34	53	8	ND	83	22	19
<i>n</i> -dodecane	6	9	6	BDL	ND	44	13	27
<i>n</i> -tridecane	70	87	168	BDL	ND	288	66	70
<i>n</i> -tetradecane	17	26	55	BDL	ND	77	24	60
<i>n</i> -pentadecane	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	BDL	5	13	BDL	ND	103	7	23
C5	264	326	133	BDL	ND	34	30	12
C6	890	987	606	29	ND	174	83	231
C7	726	637	584	21	ND	517	72	117
C8	819	2,586	3,851	377	ND	1,536	560	314
C9	1,330	1,288	1,442	305	ND	1,304	405	210
C10	420	444	333	128	ND	957	299	176
C10	319	343	272	99	ND	1,185	316	238
C14	125	226	282	BDL	ND	1,003	274	197
C10	180	217	452	BDL	ND	767	183	181
C14	74	113	234	BDL	ND	767	104	173
C15	BDL	BDL	BDL	BDL	ND	257	BDL	BDL
> C15	BDL	BDL	BDL	BDL	ND	BDL	BDL	BDL
TPH	5,147	7,166	8,202	959	ND	8,604	2,333	1,872

BDL - Below detection limit.

**TABLE 14. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR INITIAL GROUNDWATER SAMPLES COLLECTED FROM 9 FEET bgs IN JUNE 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	117	41	191	BDL	BDL	BDL	17	BDL
<i>n</i> -pentane	175	190	149	BDL	BDL	BDL	BDL	BDL
2-methylpentane	114	56	64	11	BDL	BDL	5	BDL
<i>n</i> -hexane	100	52	32	8	BDL	9	BDL	5
2,4-dimethylpentane	343	175	162	14	6	10	20	40
benzene	6	559	595	57	30	20	BDL	60
<i>n</i> -heptane	54	27	20	BDL	BDL	10	16	BDL
toluene	9	11	10	5	BDL	7	BDL	37
<i>n</i> -octane	46	15	15	11	BDL	10	BDL	BDL
ethylbenzene	135	336	231	25	12	293	24	37
<i>p</i> -xylene	545	1,527	1,113	87	35	548	196	140
<i>o</i> -xylene	182	663	452	27	14	28	216	120
<i>n</i> -propylbenzene	52	31	13	BDL	BDL	28	BDL	6
<i>n</i> -decane	44	14	10	34	BDL	15	BDL	8
<i>n</i> -butylbenzene	71	47	38	7	8	442	26	17
<i>n</i> -dodecane	28	6	5	12	BDL	423	8	11
<i>n</i> -tridecane	66	90	70	BDL	14	328	53	60
<i>n</i> -tetradecane	27	41	37	BDL	BDL	67	26	31
<i>n</i> -pentadecane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	6	38	45	BDL	BDL	44	7	7
C5	264	329	291	24	153	12	12	51
C9	1,061	1,043	967	122	35	159	56	144
C9	807	568	535	26	11	214	63	134
C9	1,338	3,114	2,268	170	79	1,109	476	356
C9	1,349	1,224	796	95	75	597	3,654	207
C10	527	362	186	68	65	381	1,516	168
C11	432	328	174	9	99	585	2,282	253
C11	197	232	133	12	31	423	169	148
C13	160	238	200	BDL	14	328	154	165
C11	88	192	159	BDL	BDL	230	119	104
C10	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	6,229	7,668	5,754	526	562	4,082	6,508	1,737

BDL - below detection limit.



**TABLE 15. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR INITIAL GROUNDWATER SAMPLES COLLECTED FROM 12 FEET bgs IN JUNE 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	230	74	127	102	BDL	127	71	60
<i>n</i> -pentane	280	90	142	44	BDL	BDL	BDL	12
2-methylpentane	126	38	64	43	BDL	14	19	14
<i>n</i> -hexane	94	39	45	11	5	13	BDL	BDL
2,4-dimethylpentane	386	153	172	73	12	58	14	40
benzene	1,134	395	76	438	544	882	1,536	1,534
<i>n</i> -heptane	49	28	31	BDL	BDL	6	7	BDL
toluene	240	68	19	26	15	32	28	78
<i>n</i> -octane	32	28	10	7	12	5	BDL	BDL
ethylbenzene	620	218	371	80	39	93	44	66
<i>o</i> -xylene	2,194	1,024	1,950	281	210	220	155	243
<i>o</i> -xylene	1,054	428	844	120	85	90	123	139
<i>n</i> -propylbenzene	61	24	20	9	BDL	9	BDL	5
<i>n</i> -decane	20	14	24	81	28	BDL	5	BDL
<i>n</i> -butylbenzene	94	48	42	38	BDL	12	13	28
<i>n</i> -dodecane	10	14	6	29	8	5	12	10
<i>n</i> -tridecane	61	76	140	5	BDL	38	16	35
<i>n</i> -tetradecane	13	47	57	BDL	BDL	10	6	18
<i>n</i> -pentadecane	BDL	5	BDL	BDL	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	60	7	61	5	21	67	29	11
C6	466	166	266	134	298	127	80	108
C6	2,230	717	652	580	519	927	1,631	1,630
C7	964	471	505	103	47	262	92	176
C6	4,438	2,124	3,913	584	465	580	506	755
C9	1,554	1,012	1,422	245	136	227	209	207
C10	580	308	324	112	63	150	135	137
C14	369	327	278	60	37	135	126	161
C12	276	225	250	36	8	83	57	96
C14	157	198	386	5	BDL	92	52	89
C14	53	205	242	BDL	BDL	29	24	55
C15	BDL	5	BDL	BDL	BDL	BDL	BDL	BDL
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	11,147	5,765	8,299	1,864	1,594	2,679	2,941	3,425

BDL - below detection limit.

the system ranged from 893 to 5,242  $\mu\text{g/L}$  and from 1,594 to 11,147  $\mu\text{g/L}$  for BTEX and TPH, respectively. MP-1 was the most contaminated and MP-5 was the least contaminated with both BTEX and TPH. The data showed a trend of increasing BTEX and TPH concentrations from south to north. The hydrocarbons covered a molecular weight range from <C5 to C14 at all points except MP-4 and MP-5 where the range went to C13 and C12, respectively.

The data for the groundwater samples collected from 15 feet bgs are presented in Table 16. The average BTEX and TPH concentrations were 1,838 and 4,768  $\mu\text{g/L}$ , respectively. The concentrations of BTEX and TPH ranged from 941 to 3,828  $\mu\text{g/L}$  and 1,348 to 15,933  $\mu\text{g/L}$ , respectively. In general, the hydrocarbon levels were higher to the north of the well systems. MP-3 was the most heavily contaminated location with regards to both BTEX and TPH with the TPH level significantly higher than the other locations and the BTEX level similar to that at MP-1. The molecular weight ranges covered <C5 to C14 at all points except MP-4 and MP-5, which had hydrocarbons in the molecular weight ranges below C13. At most points, the bulk of the hydrocarbon was in molecular weight ranges below C9.

The data from all four depths showed a significant amount of hydrocarbon in the lower-molecular-weight ranges. These compounds had the potential to be stripped in the well system. The higher-molecular-weight compounds that were not stripped would be recirculated in the aquifer where biodegradation would serve as the removal mechanism.

### 3. Soil Gas JP-4 Concentrations

Soil gas samples were collected on sorbent tubes according to the method described in Section II.C.3 and were analyzed for the 19 compounds comprising the JP-4 fingerprint, for molecular weight ranges based on the number of carbons, and for TPH. The initial samples were collected from the soil gas probes at 2 and 4 feet bgs following system installation and just before the system was started. Tables 17 and 18 contain the results from the analyses for the samples from the 2- and 4-foot depths, respectively, where data below the detection limit are indicated by BDL.

The data in Table 17 show that the BTEX and TPH concentrations at the 2-foot depth ranged from 0.07 to 451 ppmv and 10.09 to 4,293 ppmv, respectively. In general, the hydrocarbon concentrations were higher to the north of the well system. MP-3 had the highest and MP-5 had the lowest concentrations of both BTEX and TPH. Hydrocarbons in the soil gas ranged in molecular weight from <C5 through C15 from all points except MP-5 which had hydrocarbons between C5 and C14. The majority of the hydrocarbons at all points fell in the C6 to C12 range.

The analytical results for the soil gas samples extracted from 4 feet bgs are presented in Table 18. The data show that the composition of the soil gas from this depth was extremely variable, with concentrations of BTEX and TPH ranging from 0.18 to 307 ppmv and 28.19 to 11,400 ppmv, respectively. The soil gas probes at 4 feet at MP-3,

**TABLE 16. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR INITIAL GROUNDWATER SAMPLES COLLECTED FROM 15 FEET bgs IN JUNE 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	232	119	40	BDL	12	57	75	BDL
<i>n</i> -pentane	284	139	119	BDL	25	16	BDL	BDL
2-methylpentane	130	58	74	6	16	7	BDL	13
<i>n</i> -hexane	100	50	69	6	7	7	BDL	5
2,4-dimethylpentane	334	150	209	18	66	11	9	22
benzene	1,150	564	83	636	1,170	770	874	876
<i>n</i> -heptane	87	32	80	BDL	BDL	8	8	7
toluene	147	36	82	16	28	17	18	29
<i>n</i> -octane	26	23	43	BDL	11	BDL	15	20
ethylbenzene	388	101	442	46	76	46	27	27
<i>p</i> -xylene	1,404	450	2,190	163	375	50	95	109
<i>p</i> -xylene	629	170	1,031	67	135	58	69	56
<i>n</i> -propylbenzene	47	13	59	BDL	5	5	BDL	BDL
<i>n</i> -decane	21	6	111	32	39	BDL	31	21
<i>n</i> -butylbenzene	36	30	165	14	BDL	16	8	12
<i>n</i> -dodecane	10	6	187	12	13	BDL	BDL	BDL
<i>n</i> -tridecane	60	22	525	BDL	BDL	16	10	19
<i>n</i> -tetradecane	21	13	440	BDL	BDL	8	7	7
<i>n</i> -pentadecane	BDL	26	70	BDL	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	79	78	BDL	21	9	57	35	45
C5	476	267	186	26	57	57	67	89
C6	1,980	918	795	606	1,344	835	933	1,059
C7	898	423	1,005	64	82	176	105	134
C8	3,140	1,092	5,151	447	759	361	332	674
C9	1,212	459	2,270	110	206	125	122	92
C10	391	154	913	46	96	74	72	47
C14	271	126	872	16	50	92	68	49
C12	186	67	1,244	12	13	47	28	36
C10	154	62	1,320	BDL	BDL	47	16	41
C14	84	50	2,107	BDL	BDL	24	7	16
C15	BDL	26	70	BDL	BDL	BDL	BDL	BDL
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	8,871	3,722	15,933	1,348	2,616	1,895	1,779	1,982

BDL - Below detection limit.

**TABLE 17. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (ppmv) FOR INITIAL SOIL GAS SAMPLES COLLECTED FROM 2 FEET bgs IN JUNE 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.03	BDL	0.03	0.03	BDL	0.01	0.09	0.02
<i>n</i> -pentane	0.04	0.02	0.03	0.06	BDL	0.07	0.09	0.04
2-methylpentane	23.47	0.86	24.10	51.50	0.02	5.28	0.13	0.34
<i>n</i> -hexane	0.15	0.01	0.28	0.90	0.02	BDL	0.09	BDL
2,4-dimethylpentane	3.54	4.04	9.60	18.43	BDL	5.16	0.13	2.59
benzene	5.23	1.64	9.08	21.67	BDL	5.53	0.01	0.08
<i>n</i> -heptane	126.42	0.95	9.68	19.74	0.02	1.05	0.04	0.12
toluene	17.08	95.18	395.87	198.35	0.04	37.13	1.21	11.80
<i>n</i> -octane	45.62	6.57	43.43	17.04	BDL	27.01	0.45	8.84
ethylbenzene	8.84	4.93	15.83	4.63	0.01	14.22	0.84	5.41
<i>p</i> -xylene	19.96	1.09	11.46	2.41	0.02	14.17	0.19	2.50
<i>o</i> -xylene	2.62	5.42	18.80	2.35	BDL	4.78	0.41	1.71
<i>n</i> -propylbenzene	4.62	3.17	3.29	1.72	0.04	51.51	2.84	16.62
<i>n</i> -decane	28.78	3.61	4.88	0.77	0.09	5.70	2.26	2.24
<i>n</i> -butylbenzene	1.70	1.18	2.51	0.44	0.02	4.57	2.07	1.27
<i>n</i> -dodecane	3.83	1.33	0.72	0.56	0.11	3.15	1.68	1.49
<i>n</i> -tridecane	0.35	0.34	0.06	0.10	0.04	0.26	0.19	0.22
<i>n</i> -tetradecane	0.02	0.01	0.01	0.02	BDL	BDL	0.09	0.02
<i>n</i> -pentadecane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	0.56	0.43	0.7	0.42	BDL	0.36	0.17	0.17
C5	23.51	1.02	10.89	4.76	0.03	1.76	0.49	0.31
C9	241.22	20.51	235.85	544.01	0.09	43.04	2.44	8.99
C9	1,098.2	411.6	2,463.6	2,142.2	0.09	595.57	7.76	83.64
C9	725.84	246.3	1,185.3	369.6	0.32	539.02	22.66	161.39
C9	296.60	157.9	228.7	53.05	0.53	533.37	67.25	157.22
C12	236.06	105.3	113.98	32.88	1.46	458.17	102.58	116.35
C12	112.5	43.17	37.7	13.4	2.66	219.78	64.99	57.71
C12	36.1	25.23	13.26	8.41	2.99	82.63	42.52	31.40
C13	7.43	10.55	3.09	4.59	1.66	20.33	18.58	12.19
C14	0.97	1.91	0.34	1.09	0.26	1.90	3.18	1.72
C15	0.06	0.07	0.05	0.09	BDL	0.07	0.07	0.05
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	2,779	1,024	4,293	3,174	10.09	2,496	322.7	631.1

BDL - Below detection limit.

**TABLE 18. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (ppmv) FOR INITIAL SOIL GAS SAMPLES COLLECTED FROM 4 FEET bgs IN JUNE 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.11	0.04	ND	ND	0.08	ND	0.10	0.03
<i>n</i> -pentane	0.37	0.33	ND	ND	0.02	ND	0.07	0.02
2-methylpentane	130.32	28.77	ND	ND	0.06	ND	9.58	1.09
<i>n</i> -hexane	1.56	0.17	ND	ND	0.03	ND	0.07	0.03
2,4-dimethylpentane	15.29	8.24	ND	ND	0.02	ND	3.51	3.45
benzene	0.08	8.84	ND	ND	0.02	ND	4.39	2.47
<i>n</i> -heptane	718.85	112.32	ND	ND	0.07	ND	9.28	0.87
toluene	69.71	234.49	ND	ND	0.09	ND	10.26	16.09
<i>n</i> -octane	135.42	89.41	ND	ND	0.02	ND	17.24	16.83
ethylbenzene	33.14	20.35	ND	ND	0.02	ND	7.43	7.27
<i>p</i> -xylene	75.31	31.36	ND	ND	0.03	ND	7.40	5.82
<i>o</i> -xylene	44.19	12.08	ND	ND	0.02	ND	6.31	2.77
<i>n</i> -propylbenzene	26.06	5.94	ND	ND	0.17	ND	24.99	6.23
<i>n</i> -decane	6.1	30.22	ND	ND	0.12	ND	6.20	3.69
<i>n</i> -butylbenzene	3.65	1.67	ND	ND	0.08	ND	1.81	1.33
<i>n</i> -dodecane	3.07	2.62	ND	ND	0.29	ND	1.89	1.46
<i>n</i> -tridecane	0.19	0.27	ND	ND	0.09	ND	0.18	0.28
<i>n</i> -tetradecane	BDL	0.12	ND	ND	0.03	ND	BDL	0.01
<i>n</i> -pentadecane	BDL	BDL	ND	ND	BDL	ND	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	2.68	1.2	ND	ND	0.11	ND	4.47	0.26
C5	218.08	27.23	ND	ND	0.32	ND	29.69	0.80
C5	1,355.41	299.96	ND	ND	0.82	ND	77.30	20.66
C9	4,388.98	1,988.55	ND	ND	0.60	ND	223.33	176.30
C5	3,411.45	1,393.59	ND	ND	0.48	ND	280.04	273.05
C9	1,222.94	411.17	ND	ND	2.04	ND	291.48	206.06
C14	586.35	266.91	ND	ND	5.50	ND	222.43	140.70
C14	170.98	96.69	ND	ND	6.52	ND	99.41	61.67
C12	38.46	25.01	ND	ND	7.03	ND	40.86	26.85
C13	5.08	6.73	ND	ND	4.01	ND	13.30	8.59
C14	0.49	3.93	ND	ND	0.76	ND	1.37	1.26
C15	0.02	0.4	ND	ND	BDL	ND	0.02	0.02
> C15	BDL	BDL	ND	ND	BDL	ND	BDL	BDL
TPH	11,400.92	4,521.37	ND	ND	28.19	ND	1,283.70	916.22

BDL - Below detection limit.

ND - No data because of water in soil gas probe.

MP-4, and MP-6 contained water, and it was not possible to collect a sorbent tube sample from these points. The no data indication is shown on Table 18 as ND. In general, the BTEX and TPH concentrations were significantly higher on the north side of the well systems. Both the BTEX and TPH concentrations were highest at MP-1 and lowest at MP-5. Hydrocarbons in molecular weight ranges from <C5 to C15 were detected in all samples except MP-5, in which no C15 hydrocarbons were detected.

## **B. DISSOLVED OXYGEN AND CONDUCTIVITY RESULTS**

Dissolved oxygen was monitored in all of the 32 groundwater monitoring probes to track the delivery of oxygen through the recirculation of oxygenated water by the well systems (data not shown). In general, the water entering the well systems contained less than 1.0 mg/L DO. The air lift/air stripping action of the well systems was effective at oxygenating the water, with DO levels in the water exiting the well typically greater than 5.0 mg/L. During the 12 months of system operation, there was no apparent increase in dissolved oxygen at any of the groundwater monitoring point locations.

Conductivity measurements on groundwater samples collected from the groundwater monitoring points at the four depths at the eight locations were used to trace the movement of the bromide tracer in the aquifer. Three sets of complete samples were collected, and the data are presented in Table 19. Additional samples were taken from the sampling probes associated with the upper and lower screens immediately following the addition of the NaBr solution.

The conductivity in the water collected from the probes associated with the upper and lower screens indicated that the communication time between the two screens was less than 2 minutes, the amount of time required to collect the first sample. The conductivity of the water collected 2 minutes following addition was 279  $\mu$ S, up from the initial conductivity of 187  $\mu$ S. The conductivity at the lower screen was 19,900  $\mu$ S 30 minutes following salt addition. The conductivity at the upper screen immediately went off scale and remained off scale for more than 30 minutes.

Continuous sampling continued on groundwater from all of the 32 monitoring probes for approximately 8 hours following salt addition. There was no evidence of increased conductivity at any of the points by the end of this 8-hour period.

Groundwater samples were collected after 3 months of system operation, and conductivity measurements were made. The data were recorded and are presented in Table 19. The data showed significantly elevated conductivity levels at all sampling locations throughout the treatment area. Prior to salt addition, the average initial conductivity was 245  $\mu$ S and the range was between 99 and 520  $\mu$ S. After 3 months, the average conductivity was 9,391  $\mu$ S and the range was between 3,910 and 17,150  $\mu$ S.

**TABLE 19. CONDUCTIVITY DATA ( $\mu$ S) FOR GROUNDWATER SAMPLES COLLECTED DURING THE IN-WELL AIR STRIPPING/ BIOVENTING STUDY AT TYNDALL AFB, FLORIDA**

Monitor Point ID	Months of Operation		
	Initial*	3 Months	7 Months
<b>6-Foot Depth</b>			
1	299	ND	1,037
2	287	4,990	456
3	277	8,260	227
4	361	9,280	141
5	529	3,910	403
6	500	7,800	249
7	319	10,820	261
6	194	15,400	368
<b>9-Foot Depth</b>			
1	282	11,790	420
2	196	12,530	399
3	137	6,940	127
4	258	7,910	130
5	420	7,990	247
6	386	17,150	294
7	311	11,510	253
6	213	5,340	342
<b>12-Foot Depth</b>			
1	230	12,930	200
2	325	7,370	201
3	215	8,430	235
4	159	9,300	132
6	231	6,910	261
6	181	10,820	258
7	166	13,320	216
6	132	9,480	157
<b>15-Foot Depth</b>			
1	111	8,450	328
2	118	8,320	174
3	ND	10,290	ND
4	99	4,690	64
5	273	7,430	278
6	159	13,790	183
7	118	9,400	120
8	131	8,780	133

ND - No data due to probe clogging.

\*Initial conductivity before tracer addition.

A final set of groundwater samples was collected and analyzed for conductivity after 7 months of system operation, 3 months of the MBW system, and 4 months of the mKGB system. The data indicate that the conductivity levels significantly decreased from the levels seen after 3 months of operation. The conductivities were approaching the initial background levels with an average of 267  $\mu\text{S}$  and a range of 64 to 1,037  $\mu\text{S}$ .

## **C. SHUTDOWN/RESPIRATION TESTS**

### **1. Shutdown/Respiration Test 1 (20 September through 3 October 1994)**

#### **a. Surface Emission Testing**

Surface flux measurements were made by collecting emission gas samples according to the methods described in Sections II.C.4 and II.D.4. The gas samples were collected on sorbent tubes and analyzed for the 19 compounds comprising the JP-4 fingerprint, for molecular weight ranges based on the number of carbons, and for TPH. Samples were pulled at 5-, 12½-, and 25-foot distances from the well system during operation and when the system was turned off. The concentration data were used to calculate flux rates at each distance and the averaged flux rate was used to calculate a total emission rate. The results from these calculations are presented in Table 20.

The data show that the flux rates of the 19 specific hydrocarbon compounds when the in-well air stripping system was operating at 1.0 cfm were all below the detection limit and that the TPH flux rates ranged from 0.097  $\mu\text{g}/\text{m}^2\cdot\text{min}$  at the 5-foot distance to 0.18  $\mu\text{g}/\text{m}^2\cdot\text{day}$  at the 25-foot distance when the system was operating. The molecular weight data indicated that the hydrocarbons being emitted were in the <C5 to C11 range. After the system was turned off for several days, the TPH flux rate increased significantly and BTEX constituents were detected at each distance. The total emission rate was calculated for each compound, for molecular weight range, and for TPH, using the average flux value from the three points and assuming a 25-foot radius of influence. When the system was off, the total emission rate of BTEX was approximately 36  $\mu\text{g}/\text{min}$  and the total TPH emission rate was approximately 465  $\mu\text{g}/\text{min}$ . BTEX emission accounted for approximately 7.7 percent of the TPH that was being emitted. The molecular weight data indicated that the hydrocarbons being emitted when the system was off fell in the C11 range and below, with the majority in the C6 to C7 range.

#### **b. Groundwater Sample Analyses**

Groundwater samples were collected in September immediately prior to shutting off the MBW system. The samples were analyzed for the 19 specific compounds that comprise the JP-4 fingerprint, for molecular weight ranges based on number of carbon atoms, and for TPH. The results from these analyses are presented in Tables 21, 22, 23, and 24. Readings below the detection level are indicated by BDL in the tables.



**TABLE 20. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA FOR SURFACE EMISSIONS IN SEPTEMBER 1994**

Compound	Flux Rate (μg/m <sup>2</sup> •min)						Total Emission (μg/min)	
	5 Feet		12½ feet		25 feet			
	On	Off	On	Off	On	Off	On	Off
Isopentane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -pentane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
2-methylpentane	BDL	BDL	BDL	0.42	BDL	0.031	0.00	27.41
<i>n</i> -hexane	BDL	BDL	BDL	0.051	BDL	0.020	0.00	4.32
2,4-dimethylpentane	BDL	BDL	BDL	0.13	BDL	0.024	0.00	9.36
benzene	BDL	BDL	BDL	0.13	BDL	0.060	0.00	11.55
<i>n</i> -heptane	BDL	BDL	BDL	0.071	BDL	0.031	0.00	6.20
toluene	BDL	0.088	BDL	0.23	BDL	0.013	0.00	20.12
<i>n</i> -octane	BDL	BDL	BDL	0.031	BDL	0.024	0.00	3.34
ethylbenzene	BDL	BDL	BDL	0.015	BDL	BDL	0.00	0.91
<i>p</i> -xylene	BDL	BDL	BDL	0.031	BDL	0.011	0.00	2.55
<i>o</i> -xylene	BDL	BDL	BDL	0.011	BDL	BDL	0.00	0.67
<i>n</i> -propylbenzene	BDL	BDL	BDL	BDL	BDL	0.013	0.00	0.78
<i>n</i> -decane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -butylbenzene	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -dodecane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -tridecane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -tetradecane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -pentadecane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
Molecular Weight Ranges								
< C5	0.020	0.051	0.040	0.091	0.033	0.029	5.65	10.40
C5	0.038	0.062	0.022	0.064	0.040	0.097	6.07	13.55
C6	0.011	0.027	0.015	1.60	0.015	0.71	2.50	142.09
C7	BDL	0.024	0.013	3.52	0.013	0.73	1.59	259.87
C8	0.011	0.022	0.009	0.29	0.024	0.062	2.68	22.75
C9	BDL	0.088	0.002	0.018	0.007	0.018	0.55	7.53
C14	0.018	0.020	0.009	0.024	0.038	0.029	3.96	4.43
C12	BDL	BDL	BDL	BDL	0.009	0.009	0.55	0.55
C12	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
C13	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
C14	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
C15	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
> C15	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
TPH	0.097	0.22	0.11	5.71	0.18	1.71	23.53	464.52

BDL - Below detection limit.

Table 21 contains the results from the analyses of groundwater samples from the 6-foot depth. Samples were collected from all probes except MP-3, which was clogged. The results show that the averaged BTEX and TPH concentrations at 6 feet bgs were 398.1 and 2,919.6  $\mu\text{g/L}$ , respectively. The averaged BTEX accounted for slightly less than 14 percent of the TPH at the 6-foot depth. BTEX levels ranged from 3  $\mu\text{g/L}$  at MP-5 to 1,201  $\mu\text{g/L}$  at MP-2. TPH concentrations ranged from 308 to 5,163  $\mu\text{g/L}$  at MP-5 and MP-2, respectively. Also of interest was the detection of *n*-tridecane and *n*-tetradecane at concentrations that were higher than were measured in the initial groundwater samples. The molecular weight data show that the majority of the hydrocarbon on the north side of the well system (MP-1, MP-2, and MP-4) fell in the C6 to C14 range and on the south side of the well system (MP-5, MP-6, MP-7, and MP-8) fell more in the range from C8 to C14.

The analytical results for groundwater from the 9-foot depth are presented in Table 22. The data indicate that this depth was more contaminated than the 6-foot depth, with averaged BTEX and TPH concentrations of 749 and 3,073  $\mu\text{g/L}$ , respectively. The averaged BTEX accounted for over 24 percent of the TPH at this depth. The concentrations ranged from below detection to 2,214  $\mu\text{g/L}$  for BTEX and from 115 to 7,481  $\mu\text{g/L}$  for TPH. In general, the groundwater from probes north of the well systems was more contaminated than the groundwater from the probes to the south. The molecular weight data show that the hydrocarbon in the groundwater on the northern side of the system was slightly lighter with the majority of the hydrocarbon in the C5 to C14 range versus the C7 to C14 range on the southern side.

Groundwater from the 12-foot depth contained the highest level of BTEX and TPH among the four depths sampled, with averaged concentrations of 1,610 and 5,005  $\mu\text{g/L}$ , respectively (Table 23). The averaged BTEX accounted for just over 32 percent of the TPH. BTEX and TPH concentrations ranged from below detection to 5,601  $\mu\text{g/L}$  and 84 to 9,875  $\mu\text{g/L}$ , respectively. MP-5 was characterized with the lowest BTEX and TPH concentrations. MP-8 had the highest BTEX concentration and MP-2 had the highest TPH concentration. The BTEX at MP-8 accounted for over 60 percent of the TPH, a significantly higher fraction than average at this depth. In general, the groundwater on the northern side of the well system was more contaminated with TPH than the groundwater on the southern side. The exception was MP-8, which was characterized with 9,285  $\mu\text{g/L}$ , the second highest TPH concentration at the 12-foot depth. The molecular weight data showed that groundwater from the points to the north of the well system and MP-8 contained significantly higher concentrations of hydrocarbons in the C5 to C9 range.

Groundwater samples were collected from seven of the eight probes at the 15-foot depth; the analytical results are presented in Table 24. The averaged BTEX and TPH concentrations were 1,444 and 3,519  $\mu\text{g/L}$ , respectively. The averaged BTEX concentration accounted for over 41 percent of the average TPH. BTEX and TPH concentrations ranged from below detection limits to 3,960  $\mu\text{g/L}$  and from 234 to 9,302  $\mu\text{g/L}$ , respectively. The lowest BTEX and TPH concentrations were detected at MP-5, whereas the highest were detected at MP-1. Although MP-1 and MP-2 were the most contaminated, the trend in increasing contamination was less apparent than at the other

**TABLE 21. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 6 FEET bgs IN SEPTEMBER 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	3	ND	BDL	BDL	BDL	BDL	BDL
<i>n</i> -pentane	7	15	ND	BDL	BDL	BDL	20	BDL
2-methylpentane	BDL	13	ND	4	BDL	BDL	BDL	BDL
<i>n</i> -hexane	3	12	ND	3	BDL	BDL	BDL	BDL
2,4-dimethylpentane	7	BDL	ND	33	BDL	BDL	7	15
benzene	19	12	ND	BDL	BDL	BDL	BDL	4
<i>n</i> -heptane	21	29	ND	BDL	BDL	BDL	BDL	BDL
toluene	3	8	ND	3	BDL	2	BDL	11
<i>n</i> -octane	6	12	ND	3	BDL	7	2	1
ethylbenzene	16	84	ND	112	BDL	136	21	37
<i>p</i> -xylene	161	758	ND	426	1	19	94	157
<i>o</i> -xylene	60	339	ND	37	2	24	89	152
<i>n</i> -propylbenzene	7	17	ND	24	3	38	3	5
<i>n</i> -decane	8	18	ND	9	2	14	3	6
<i>n</i> -butylbenzene	17	39	ND	33	10	50	37	13
<i>n</i> -dodecane	36	39	ND	2	BDL	16	30	25
<i>n</i> -tridecane	29	146	ND	65	31	362	120	104
<i>n</i> -tetradecane	24	32	ND	13	10	317	160	107
<i>n</i> -pentadecane	10	3	ND	BDL	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	15	3	ND	4	4	7	5	3
C5	8	21	ND	12	BDL	BDL	56	BDL
C5	53	126	ND	60	BDL	28	9	39
C7	124	236	ND	140	BDL	27	14	60
C5	539	2,039	ND	674	4	248	234	386
C7	319	1,024	ND	657	41	513	282	201
C10	171	303	ND	324	57	2,754	228	171
C14	262	407	ND	254	81	463	483	235
C12	182	295	ND	171	21	535	359	209
C13	118	318	ND	164	56	1,114	312	261
C14	115	347	ND	58	43	701	343	232
C15	25	44	ND	BDL	BDL	2	3	BDL
> C15	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL
TPH	1,931	5,163	ND	2,518	308	6,391	2,329	1,797

BDL - Below detection limit.

ND - No data because of water in soil gas probe.

**TABLE 22. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 9 FEET bgs IN SEPTEMBER 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	95	93	BDL	BDL	BDL	BDL	BDL
<i>n</i> -pentane	BDL	98	74	BDL	BDL	BDL	11	BDL
2-methylpentane	BDL	39	49	BDL	BDL	BDL	BDL	BDL
<i>n</i> -hexane	BDL	34	31	BDL	BDL	BDL	BDL	BDL
2,4-dimethylpentane	BDL	218	200	4	BDL	BDL	3	23
benzene	BDL	18	200	BDL	BDL	3	BDL	2
<i>n</i> -heptane	BDL	23	14	BDL	BDL	BDL	BDL	BDL
toluene	5	9	17	2	BDL	3	BDL	11
<i>n</i> -octane	4	9	8	2	3	6	2	6
ethylbenzene	8	297	326	103	BDL	208	11	38
<i>p</i> -xylene	7	1,572	1,201	164	BDL	266	57	184
<i>o</i> -xylene	5	555	470	16	BDL	40	56	142
<i>n</i> -propylbenzene	3	13	20	21	BDL	51	2	6
<i>n</i> -decane	4	19	17	8	3	17	3	6
<i>n</i> -butylbenzene	4	40	19	23	2	61	31	15
<i>n</i> -dodecane	4	25	25	3	BDL	29	11	20
<i>n</i> -tridecane	4	147	127	56	12	368	86	137
<i>n</i> -tetradecane	9	66	92	12	8	257	129	148
<i>n</i> -pentadecane	BDL	22	15	BDL	BDL	8	BDL	37
<b>Molecular Weight Ranges</b>								
< C5	2	BDL	6	4	5	3	6	8
C5	BDL	173	143	BDL	BDL	BDL	45	BDL
C6	0	605	721	14	5	47	5	68
C7	27	343	367	107	BDL	83	10	77
C8	81	3,042	2,292	332	3	633	145	417
C9	47	1,384	1,090	468	18	1,046	225	225
C10	10	413	269	232	10	518	174	148
C11	26	419	278	211	30	639	335	242
C12	4	360	219	131	9	683	168	250
C13	16	351	335	136	35	927	192	411
C14	8	294	212	51	BDL	572	276	382
C15	BDL	96	47	BDL	BDL	28	BDL	117
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	221	7,481	5,979	1,686	115	5,178	1,581	2,346

BDL - Below detection limit.

**TABLE 23. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 12 FEET bgs IN SEPTEMBER 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	178	190	BDL	BDL	BDL	6	6	115
<i>n</i> -pentane	216	201	BDL	BDL	BDL	BDL	4	64
2-methylpentane	108	90	23	BDL	BDL	8	BDL	55
<i>n</i> -hexane	112	80	15	BDL	BDL	9	BDL	21
2,4-dimethylpentane	479	385	84	BDL	BDL	BDL	16	176
benzene	3	54	28	BDL	BDL	206	15	2,551
<i>n</i> -heptane	45	38	18	BDL	BDL	5	BDL	6
toluene	9	19	21	2	BDL	4	BDL	276
<i>n</i> -octane	25	20	37	2	BDL	4	BDL	2
ethylbenzene	95	448	329	90	BDL	60	25	452
<i>p</i> -xylene	396	1,967	1,207	37	BDL	67	126	1,642
<i>o</i> -xylene	147	798	898	14	BDL	103	107	680
<i>n</i> -propylbenzene	77	53	16	21	BDL	43	4	23
<i>n</i> -decane	22	35	18	7	2	11	3	8
<i>n</i> -butylbenzene	59	42	23	23	2	40	17	17
<i>n</i> -dodecane	8	23	22	1	BDL	10	7	5
<i>n</i> -tridecane	107	129	313	50	9	337	51	80
<i>n</i> -tetradecane	29	75	230	8	BDL	195	50	73
<i>n</i> -pentadecane	BDL	19	5	BDL	BDL	BDL	BDL	9
<b>Molecular Weight Ranges</b>								
< C5	3	2	2	5	26	6	3	40
C5	357	347	BDL	BDL	BDL	8	8	320
C8	1,265	1,124	446	8	BDL	244	33	2,769
C7	780	651	246	66	BDL	132	16	574
C8	1,004	3,965	2,951	159	BDL	303	273	3,370
C9	1,818	1,773	1,482	421	13	695	277	825
C10	540	525	322	231	3	359	188	474
C11	394	348	301	200	3	511	245	266
C12	121	347	362	132	17	324	131	258
C11	289	297	764	118	9	875	148	207
C14	93	343	520	31	10	440	103	156
C10	BDL	152	39	BDL	3	4	BDL	26
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	6,664	9,875	7,434	1,371	84	3,901	1,425	9,285

BDL - Below detection limit.

**TABLE 24. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (µg/L) FOR GROUNDWATER SAMPLES COLLECTED FROM 15 FEET bgs IN SEPTEMBER 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	59	89	BDL	25	10	45	ND	71
<i>n</i> -pentane	120	90	BDL	12	7	20	ND	28
2-methylpentane	87	56	BDL	9	BDL	17	ND	BDL
<i>n</i> -hexane	90	59	BDL	7	59	15	ND	3
2,4-dimethylpentane	283	14	BDL	31	BDL	BDL	ND	58
benzene	570	863	BDL	85	BDL	302	ND	1,455
<i>n</i> -heptane	61	36	15	BDL	BDL	10	ND	40
toluene	6	14	6	3	BDL	3	ND	35
<i>n</i> -octane	22	6	35	3	2	4	ND	27
ethylbenzene	551	219	8	59	BDL	212	ND	589
<i>p</i> -xylene	1,941	968	61	177	BDL	332	ND	5
<i>o</i> -xylene	892	418	117	8	BDL	99	ND	109
<i>n</i> -propylbenzene	56	182	3	3	5	25	ND	33
<i>n</i> -decane	24	15	42	19	3	11	ND	3
<i>n</i> -butylbenzene	40	31	4	24	5	28	ND	12
<i>n</i> -dodecane	13	10	8	4	BDL	5	ND	8
<i>n</i> -tridecane	45	49	34	BDL	17	146	ND	22
<i>n</i> -tetradecane	13	23	39	BDL	BDL	101	ND	23
<i>n</i> -pentadecane	5	14	BDL	BDL	BDL	BDL	ND	BDL
<b>Molecular Weight Ranges</b>								
< C5	7	29	5	4	5	18	ND	34
C5	166	173	BDL	30	7	52	ND	167
C9	1,246	1,386	14	163	67	541	ND	1,342
C9	840	464	46	54	BDL	184	ND	149
C9	4,329	2,014	383	323	7	747	ND	1,045
C9	1,416	877	346	204	28	524	ND	160
C10	551	268	116	96	20	309	ND	121
C12	374	284	164	33	48	341	ND	120
C12	193	149	52	31	22	272	ND	78
C13	125	122	92	BDL	21	397	ND	78
C14	43	107	74	BDL	8	230	ND	49
C15	13	40	BDL	BDL	BDL	BDL	ND	BDL
> C15	BDL	BDL	BDL	BDL	BDL	BDL	ND	BDL
TPH	9,302	5,912	1,291	938	234	3,615	ND	3,343

BDL - Below detection limit.

ND - No data because sampling probe clogged.

depths. In general, the molecular weight ranges reflected the BTEX profile with the majority of the hydrocarbon in the C6 to C9 range.

c. Soil Gas Sample Analyses

Soil gas samples were collected using the sorbent tube method described in Section II.C.3 in September 1994, after the system had been operating for 3 months. Samples were extracted from both the 2- and 4-foot depths and analyzed for the 19 specific compounds that comprise the JP-4 fingerprint, for molecular weight ranges based on number of carbon atoms, and for TPH. The data from the soil gas samples from 2 and 4 feet bgs are presented in Tables 25 and 26, respectively.

The hydrocarbon concentrations at both depths were significantly lower than they were in June 1994, when the system was first turned on. Averaged BTEX and TPH concentrations at the 2-foot depth were 1.28 and 13.38 ppmv, respectively. BTEX concentrations at this depth ranged from below detection limits at MP-1 to 5.71 ppmv at MP-6. TPH concentrations ranged from 0.31 to 56.96 ppmv at MP-1 and MP-6, respectively. The molecular weight range data in Table 25 indicate that the majority of the hydrocarbon in the soil gas at 2 feet bgs fell in the range between C6 to C9.

The hydrocarbon concentrations at the 4-foot depth were significantly higher than at the 2-foot depth, with the BTEX and TPH concentrations averaging 19.94 and 269.19 ppmv, respectively. BTEX and TPH concentrations at 4 feet bgs ranged from 0.13 to 93.19 ppmv and from 1.06 to 1250.92 ppmv, respectively, with the highest and lowest concentrations of both at MP-3 and MP-1, respectively. The molecular weight range data show that the hydrocarbon composition was slightly heavier than the soil gas at 2 feet, with most of the hydrocarbon falling in the C6 to C10 molecular weight range.

d. Respiration Testing

The O<sub>2</sub> and CO<sub>2</sub> data collected in the field were tabulated, graphed, and regressed, and the results are contained in Appendix A. Unexpectedly, the oxygen and carbon dioxide concentrations did not show a significant decrease over the normal 5-day duration of the respiration test. In general, it was observed that the O<sub>2</sub> concentrations in samples from all of the 16 probes fluctuated around the 17 to 21 percent level. The CO<sub>2</sub> concentrations also exhibited a fluctuating pattern; however, there was no correlation between the concentration fluctuations of O<sub>2</sub> and CO<sub>2</sub>.

A linear regression was performed on the oxygen data to determine if there was a downward trend in O<sub>2</sub> concentration, and to determine an O<sub>2</sub> utilization rate at each probe location. The regression data and a graph showing the fit of the line are included in Appendix A. The O<sub>2</sub> utilization rates were calculated as the slope of the O<sub>2</sub> concentration vs. time line and are presented in Table 27. Biodegradation rates were calculated on a hexane basis (Hinchee et al, 1992); these rates also are included in Table 27.

**TABLE 25. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR SOIL GAS SAMPLES COLLECTED FROM 2 FEET bgs IN SEPTEMBER 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	0.09	0.09	BDL	BDL	BDL	BDL
<i>n</i> -pentane	BDL	0.02	BDL	BDL	BDL	BDL	BDL	BDL
2-methylpentane	BDL	BDL	BDL	BDL	BDL	0.20	0.06	0.02
<i>n</i> -hexane	BDL	0.04	BDL	0.03	BDL	0.02	0.02	BDL
2,4-dimethylpentane	BDL	0.02	BDL	BDL	BDL	0.78	0.20	0.02
benzene	BDL	0.02	0.01	BDL	BDL	0.07	0.02	0.03
<i>n</i> -heptane	BDL	1.47	0.54	0.09	BDL	0.03	2.03	0.06
toluene	BDL	0.98	0.85	0.3	0.02	3.28	1.43	0.08
<i>n</i> -octane	BDL	0.04	0.10	0.12	0.01	1.12	0.72	0.04
ethylbenzene	BDL	0.04	0.04	0.06	0.02	0.57	0.21	0.02
<i>p</i> -xylene	BDL	0.11	0.04	0.09	0.07	0.75	0.12	0.04
<i>o</i> -xylene	BDL	0.03	0.06	0.06	0.03	0.50	0.24	0.02
<i>n</i> -propylbenzene	BDL	0.02	0.02	0.03	0.02	0.17	0.02	0.02
<i>n</i> -decane	BDL	0.01	0.01	BDL	BDL	0.16	0.03	BDL
<i>n</i> -butylbenzene	BDL	BDL	0.01	BDL	0.02	0.07	0.03	BDL
<i>n</i> -dodecane	BDL	BDL	0.01	BDL	0.01	BDL	BDL	BDL
<i>n</i> -tridecane	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL
<i>n</i> -tetradecane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
<i>n</i> -pentadecane	BDL	BDL	BDL	0.02	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	0.09	0.14	0.09	0.03	0.01	0.12	0.11	0.15
C5	0.20	0.42	0.09	0.09	BDL	0.19	0.34	0.39
C6	BDL	0.07	0.01	0.03	BDL	4.34	1.43	0.10
C7	0.02	3.30	3.19	1.29	0.11	20.09	12.30	0.54
C8	BDL	1.13	1.94	1.74	0.38	25.21	10.43	0.51
C9	BDL	0.05	0.09	0.12	0.31	4.59	2.74	0.09
C10	BDL	0.06	0.14	0.06	0.48	2.23	0.78	0.03
C11	BDL	BDL	0.01	BDL	0.38	0.17	0.05	BDL
C12	BDL	BDL	0.01	BDL	0.20	0.02	BDL	BDL
C13	BDL	BDL	0.01	BDL	0.02	BDL	BDL	BDL
C14	BDL	BDL	0.02	BDL	0.05	BDL	BDL	BDL
C15	BDL	BDL	BDL	0.06	3.66	BDL	BDL	BDL
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	0.31	5.17	5.60	3.42	5.60	56.96	28.18	1.80

BDL - Below detection limit.



**TABLE 26. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (ppmv) FOR SOIL GAS SAMPLES COLLECTED FROM 4 FEET bgs IN SEPTEMBER 1994**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	BDL	0.09	BDL	0.30	0.06	BDL
<i>n</i> -pentane	BDL	0.01	0.02	BDL	BDL	0.03	BDL	0.02
2-methylpentane	BDL	0.01	0.05	BDL	BDL	3.59	0.06	0.28
<i>n</i> -hexane	0.02	0.04	0.04	BDL	0.02	0.15	0.03	0.18
2,4-dimethylpentane	BDL	0.05	0.44	BDL	0.02	3.17	0.23	0.30
benzene	BDL	0.13	0.03	0.01	BDL	0.25	0.02	0.04
<i>n</i> -heptane	0.02	10.45	0.33	0.45	0.02	0.19	2.70	0.13
toluene	0.04	11.59	51.62	1.22	3.14	16.56	2.74	6.80
<i>n</i> -octane	0.02	1.04	9.38	0.41	1.35	2.16	1.39	1.49
ethylbenzene	0.02	0.47	16.38	0.17	2.98	3.08	0.59	2.06
<i>p</i> -xylene	0.05	0.22	15.24	0.32	2.84	1.79	0.75	2.331
<i>p</i> -xylene	0.02	0.35	9.92	0.21	2.43	1.22	0.64	1.21
<i>n</i> -propylbenzene	0.02	0.02	3.32	0.02	1.41	1.57	0.03	1.39
<i>n</i> -decane	BDL	0.04	2.00	0.03	0.72	0.16	0.19	0.19
<i>n</i> -butylbenzene	BDL	0.05	0.28	0.02	0.23	0.06	0.02	0.05
<i>n</i> -dodecane	BDL	BDL	0.01	BDL	0.04	BDL	BDL	0.01
<i>n</i> -tridecane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
<i>n</i> -tetradecane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
<i>n</i> -pentadecane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	0.12	0.11	0.22	0.11	0.05	0.56	0.11	0.26
C5	0.34	0.54	0.26	0.09	0.04	1.25	0.22	0.65
C8	0.02	0.25	2.82	0.01	0.16	36.55	1.78	3.68
C8	0.16	45.80	434.19	5.63	28.14	196.43	20.23	41.82
C8	0.39	26.36	655.05	8.29	67.70	134.50	24.62	71.44
C9	0.03	1.84	101.14	0.75	34.30	39.71	8.38	30.59
C14	BDL	1.09	51.38	0.36	24.04	14.25	3.82	13.77
C12	BDL	0.10	5.43	0.01	6.08	1.03	0.65	2.25
C12	BDL	BDL	0.43	BDL	0.87	0.07	0.04	0.12
C13	BDL	BDL	BDL	BDL	0.05	BDL	BDL	BDL
C14	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
> C15	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TPH	1.06	76.09	1,250.92	15.25	161.43	424.35	59.85	164.58

BDL - Below detection limit.

**TABLE 27. OXYGEN UTILIZATION RATES (%/HOUR) AND BIODEGRADATION RATES (mg/kg/day) CALCULATED FROM O<sub>2</sub> DATA COLLECTED DURING THE FIRST IN SITU RESPIRATION TEST**

Monitoring Point ID	2-Foot Depth		4-Foot Depth	
	O <sub>2</sub> Utilization Rate (percent/hr)	Biodegradation Rate (mg/kg/day)	O <sub>2</sub> Utilization Rate (percent/hr)	Biodegradation Rate (mg/kg/day)
1	0.0037	0.0932	0.0006	0.0106
2	0.0107	0.2060	0.0006	0.0158
4	0.0100	0.1923	0.0027	0.0520
4	0.0062	0.1192	0.0061	0.1172
5	0.0068	0.1302	0.0053	0.1026
6	0.0087	0.1667	0.0006	0.0182
7	0.0123	0.2360	0.0044	0.0843
8	0.0089	0.1775	0.0063	0.1205
Average	0.0086	0.1651	0.0034	0.0652

Although there was an apparent downward trend in the O<sub>2</sub> concentration over time in the gas from each of the soil gas monitoring probes, the data indicate that the activity was very low. In general the area to the south of the well system was the more active area, with biodegradation rates ranging from 0.0843 to 0.2360 mg-TPH/kg-soil/day at MP-7 at the 4-foot and 2-foot depths, respectively. These rates were much lower than expected, and it was suspected that there was a problem with the sampling or analytical equipment. Upon examination, it was discovered that there was a leak in the seal on the vacuum trap. The leak resulted in pulling ambient air into the Tedlar™ bags, thus diluting the sample. Because of this, the respiration data were not representative of the actual microbial activity.

## 2. Shutdown/Respiration Test 2 (10 through 24 January 1995)

### a. Surface Emission Testing

A second surface emission test was conducted in January 1995, to measure the hydrocarbons being emitted during operation of the mKGB well system. Emissions were measured according to the method described in Sections II.C.4 and II.D.4. Hydrocarbon

emissions were collected using sorbent tubes which were then analyzed for the 19 specific compounds comprising the JP-4 fingerprint, for molecular weight ranges based on the number of carbon atoms, and for TPH. The resulting concentrations were used to calculate flux rates for each of the three distances with and without the system running. The flux rates were averaged and a total emission rate was calculated assuming a 25-foot radius of influence. The results of the above calculations are presented in Table 28.

The data show that there was a higher flux of hydrocarbon from the ground surface when the system was operating. When the system was turned on, BTEX constituents were detected at the 5- and 12½-foot distances but not at the 25-foot distance. After the system was shut off for several days, no BTEX emissions were detected. TPH emissions were detected both with and without the system running. The total emission rates were when the system was operating were approximately 8.22 and 224 µg/min for BTEX and TPH, respectively. After the system was turned off, the total emission rates dropped to below detection limits and approximately 63 µg/min for BTEX and TPH, respectively. The molecular weight data indicated that there was a significant amount of TPH in the C15 range that was emitted both with the system on and off. Other than this fraction, the majority of the TPH was in the C11 and lower range with the system on and was distributed throughout the molecular weight range with the system off.

b. Groundwater Sample Analyses

Groundwater samples were collected from the 6-, 9-, 12-, and 15-foot-depth in January 1995, prior to shutting off the system to conduct the second respiration test. The samples were analyzed for the 19 compounds comprising the JP-4 fingerprint, for molecular weight ranges based on number of carbon atoms, and for TPH. The results from the analyses are contained in Tables 29, 30, 31, and 32.

Table 29 contains the analytical results for the groundwater samples collected from the 6-foot depth. The averaged BTEX and TPH concentrations at this depth were 494 and 2,519 µg/L, respectively. On average, the BTEX accounted for slightly less than 20 percent of the TPH. The range in BTEX and TPH concentrations were from 2.0 to 1,675 µg/L and from 225 to 5,715 µg/L, respectively. The lowest BTEX and TPH concentrations were observed at MP-5, and the highest concentrations were observed at MP-2. The BTEX and TPH concentrations on the north side of the system generally were higher than on the southern side. The molecular weight data show that the hydrocarbons to the north of the well system contained a higher proportion of the lighter fraction compounds.

Groundwater collected from the 9-foot depth was characterized with averaged BTEX and TPH concentrations of 475 and 2,836 µg/L, respectively (Table 30). The averaged BTEX concentration accounted for almost 17 percent of the averaged TPH concentration. The concentrations range from below detection to 1,828 µg/L and from 195 to 8,253 µg/L for BTEX and TPH, respectively. Groundwater from MP-5 had the lowest BTEX and TPH concentrations and MP-2 had the highest concentrations of both. In general, the concentrations of both BTEX and TPH were higher to the north of the well system. This

**TABLE 28. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA FOR SURFACE EMISSIONS IN JANUARY 1995**

Compound	Flux Rate (μg/m <sup>2</sup> ·min)						Total Emission (μg/min)	
	5 Feet		12½ feet		25 feet		On	Off
	On	Off	On	Off	On	Off		
Isopentane	BDL	0.011	0.011	BDL	BDL	0.0088	0.67	1.20
<i>n</i> -pentane	BDL	0.011	BDL	BDL	BDL	BDL	0.00	0.67
2-methylpentane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -hexane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
2,4-dimethylpentane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
benzene	0.020	BDL	BDL	BDL	BDL	BDL	1.22	0.00
<i>n</i> -heptane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
toluene	0.069	BDL	0.011	BDL	BDL	BDL	4.87	0.00
<i>n</i> -octane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
ethylbenzene	0.011	BDL	BDL	BDL	BDL	BDL	0.67	0.00
<i>p</i> -xylene	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>o</i> -xylene	0.024	BDL	BDL	BDL	BDL	BDL	1.46	0.00
<i>n</i> -propylbenzene	0.044	BDL	BDL	BDL	BDL	BDL	2.68	0.00
<i>n</i> -decane	0.18	BDL	0.060	BDL	BDL	BDL	14.59	0.00
<i>n</i> -butylbenzene	0.040	BDL	0.15	BDL	BDL	BDL	11.55	0.00
<i>n</i> -dodecane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -tridecane	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
<i>n</i> -tetradecane	BDL	0.031	0.024	0.027	0.029	BDL	3.23	3.52
<i>n</i> -pentadecane	0.071	0.23	0.11	0.13	0.035	0.13	13.13	29.79
Molecular Weight Ranges								
< C5	0.033	0.060	0.040	0.040	0.038	0.044	6.75	8.76
C8	0.0088	0.038	BDL	0.0088	0.024	0.018	1.99	3.94
C8	0.018	0.013	0.0088	0.018	0.0088	0.020	2.17	3.10
C9	0.12	0.011	0.020	0.0088	0.013	0.013	9.30	1.99
C8	0.17	0.018	0.018	0.018	0.013	0.024	12.22	3.65
C9	0.60	0.022	0.15	BDL	0.011	BDL	46.27	1.33
C10	1.56	0.029	0.17	0.015	0.020	0.011	106.39	3.34
C14	0.073	BDL	0.37	BDL	0.0066	BDL	27.34	0.00
C12	BDL	0.011	0.011	0.011	0.0044	BDL	0.93	1.33
C10	BDL	BDL	BDL	BDL	0.0022	BDL	0.13	0.00
C14	BDL	0.033	0.024	0.027	0.0044	BDL	1.73	3.65
C15	0.073	0.24	0.73	0.14	0.011	0.13	49.49	31.01
> C15	BDL	BDL	BDL	BDL	BDL	BDL	0.00	0.00
TPH	2.66	0.47	0.88	0.29	0.15	0.27	224.35	62.62

BDL - Below detection limit.

**TABLE 29. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 6 FEET bgs IN JANUARY 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	8	BDL	BDL	BDL	BDL	BDL
<i>n</i> -pentane	BDL	4	10	BDL	BDL	BDL	BDL	3
2-methylpentane	BDL	3	BDL	4	BDL	BDL	BDL	BDL
<i>n</i> -hexane	BDL	9	BDL	6	BDL	BDL	BDL	BDL
2,4-dimethylpentane	BDL	44	17	59	BDL	8	8	3
benzene	26	39	10	BDL	BDL	4	4	BDL
<i>n</i> -heptane	14	29	43	9	BDL	BDL	BDL	BDL
toluene	2	5	21	2	BDL	3	BDL	7
<i>n</i> -octane	9	28	5	5	BDL	13	3	3
ethylbenzene	12	124	94	153	BDL	71	21	24
<i>p</i> -xylene	110	1,076	194	649	2	25	90	111
<i>p</i> -xylene	56	431	362	38	BDL	27	66	96
<i>n</i> -propylbenzene	5	12	10	34	BDL	25	3	4
<i>n</i> -decane	7	13	15	11	12	11	2	4
<i>n</i> -butylbenzene	3	37	14	40	6	27	32	13
<i>n</i> -dodecane	50	66	6	4	16	15	6	31
<i>n</i> -tridecane	20	145	266	57	5	277	86	97
<i>n</i> -tetradecane	13	67	117	10	BDL	136	88	66
<i>n</i> -pentadecane	14	27	36	12	BDL	36	41	45
<b>Molecular Weight Ranges</b>								
< C5	2	3	2	BDL	BDL	BDL	BDL	11
C5	19	8	32	BDL	BDL	BDL	BDL	3
C6	44	198	181	114	BDL	27	14	64
C7	72	311	297	91	BDL	77	32	66
C8	418	2,258	1,101	956	2	189	217	270
C9	257	1,227	1,061	916	28	410	233	167
C10	97	444	316	446	44	319	185	128
C11	224	617	421	348	107	710	307	242
C12	171	352	296	62	16	171	192	220
C13	35	93	169	35	19	378	99	92
C14	18	147	252	20	9	291	182	139
C15	5	46	57	4	BDL	63	65	54
> C15	BDL	13	13	BDL	BDL	10	17	14
TPH	1,362	5,715	4,198	2,992	225	2,645	1,543	1,470

BDL - Below detection limit.

**TABLE 30. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 9 FEET bgs IN JANUARY 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	65	50	1	BDL	BDL	BDL	BDL
<i>n</i> -pentane	BDL	149	32	2	BDL	BDL	9	BDL
2-methylpentane	BDL	62	40	BDL	BDL	BDL	BDL	6
<i>n</i> -hexane	BDL	72	49	BDL	BDL	BDL	BDL	BDL
2,4-dimethylpentane	BDL	330	166	76	BDL	6	8	26
benzene	BDL	68	444	BDL	BDL	BDL	BDL	BDL
<i>n</i> -heptane	1	33	32	BDL	BDL	BDL	BDL	BDL
toluene	BDL	4	25	BDL	BDL	3	BDL	5
<i>n</i> -octane	9	45	10	7	BDL	13	2	3
ethylbenzene	4	1,721	182	5	BDL	116	15	24
<i>p</i> -xylene	6	22	380	169	BDL	37	76	131
<i>o</i> -xylene	4	13	203	4	BDL	18	64	53
<i>n</i> -propylbenzene	4	400	25	46	BDL	38	3	7
<i>n</i> -decane	2	25	10	13	34	15	8	4
<i>n</i> -butylbenzene	5	48	25	39	3	25	27	22
<i>n</i> -dodecane	4	57	22	5	7	21	15	15
<i>n</i> -tridecane	5	162	173	99	5	277	75	150
<i>n</i> -tetradecane	4	74	73	6	9	128	83	69
<i>n</i> -pentadecane	BDL	36	29	BDL	6	33	46	28
<b>Molecular Weight Ranges</b>								
< C5	2	1	6	13	BDL	BDL	BDL	BDL
C5	4	231	123	9	BDL	BDL	9	BDL
C6	BDL	900	916	119	BDL	27	13	81
C7	48	597	458	30	4	80	26	86
C8	98	2,724	971	1,160	BDL	261	189	245
C9	36	1,842	892	1,096	1	536	27	273
C10	29	589	267	454	51	217	158	189
C11	15	695	351	309	62	808	288	276
C12	3	339	230	194	25	184	175	209
C13	6	107	110	99	17	390	94	128
C14	2	172	162	20	35	268	174	160
C15	BDL	47	25	BDL	BDL	54	71	50
> C15	BDL	9	4	BDL	BDL	8	14	11
TPH	243	8,253	4,515	3,503	195	2,833	1,438	1,708

BDL - Below detection limit.

was not the case at MP-1, where the BTEX and TPH concentrations were among the lowest of the eight locations. The molecular weight data showed that the majority of the hydrocarbon covered the range from C5 to C14 on the northern half of the system and from C6 to C15 on the southern half.

The analytical results from the analyses of groundwater samples collected from the 12-foot depth in January 1995 are presented in Table 31. Average concentrations of 1,299 and 4,119  $\mu\text{g/L}$  were observed for BTEX and TPH, respectively, meaning that the BTEX accounted for over 31 percent of the TPH. The concentration ranges were from below detection to 4,991  $\mu\text{g/L}$  and from 33 to 8,860  $\mu\text{g/L}$  for BTEX and TPH, respectively. MP-5 was characterized with the lowest BTEX and TPH level and MP-8 had the highest concentration of both. The trend of increasing concentration in the northward direction was not apparent at this depth. The molecular weight data showed a similar hydrocarbon composition throughout the system, with the bulk of the contamination falling in the C6 to C12 range. The exception was MP-5 which was characterized with small amounts of hydrocarbon in the C10 to C12 range.

Groundwater samples were collected from 15 feet bgs at seven of the eight locations. The samples from this depth showed the highest level of hydrocarbon contamination (Table 32), with averaged BTEX and TPH concentrations of 1,299 and 4,119  $\mu\text{g/L}$ , respectively. On average, BTEX accounted for over 44 percent of the TPH at this depth. The ranges in concentration were from 13 to 4,540  $\mu\text{g/L}$  and 93 to 11,233  $\mu\text{g/L}$  for BTEX and TPH, respectively. MP-1 was characterized with the highest BTEX and TPH concentrations, while MP-5 was observed to have the lowest BTEX and TPH concentrations. In general, the majority of the hydrocarbon at 15 feet throughout the site fell in the range between C5 and C12.

#### c. Soil Gas Sample Analyses

Soil gas samples were collected in January 1995 from the 2- and 4-foot depths after 6 months of total system operation (3 months of the MBW system and 3 months of the modified KGB system). The samples were collected using the sorbent tube technique described in Section II.C.3, and then analyzed for the 19 specific compounds that comprise the JP-4 fingerprint, for molecular weight ranges based on the number of carbon atoms, and for TPH. The results for these analyses are presented in Tables 33 and 34.

Soil gas samples were collected from seven of the eight soil gas monitoring probes at 2 feet bgs and the analytical results are presented in Table 33. The hydrocarbon levels at this depth were significantly higher than the levels seen in the soil gas samples collected in September 1994, and lower than the initial samples collected in June 1994. The averaged BTEX and TPH concentrations were 26 and 259 ppmv, respectively. On average, the BTEX accounted for just under 10 percent of the TPH at this depth. The ranges for BTEX and TPH were from 3.0 to 79.82 ppmv and 39.93 to 684.10 ppmv, respectively. The general trend showed increasing TPH concentration from south to north. The molecular weight data revealed that the majority of the hydrocarbon contamination on the northern side

**TABLE 31. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 12 FEET bgs IN JANUARY 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	14	46	3	BDL	BDL	68	13	258
<i>n</i> -pentane	63	68	4	BDL	BDL	31	5	130
2-methylpentane	123	50	15	BDL	BDL	20	4	67
<i>n</i> -hexane	130	51	13	BDL	BDL	9	4	52
2,4-dimethylpentane	242	279	90	31	BDL	42	16	2
benzene	8	160	51	BDL	BDL	812	243	2,493
<i>n</i> -heptane	52	6	22	BDL	BDL	10	BDL	11
toluene	9	7	32	3	BDL	8	BDL	581
<i>n</i> -octane	17	9	11	655	BDL	6	2	41
ethylbenzene	23	126	347	13	BDL	84	24	291
<i>p</i> -xylene	19	260	1,579	14	BDL	235	68	1,187
<i>p</i> -xylene	8	100	901	32	BDL	165	68	439
<i>n</i> -propylbenzene	154	39	20	9	BDL	6	3	24
<i>n</i> -decane	26	17	25	50	8	5	3	16
<i>n</i> -butylbenzene	73	37	31	16	BDL	24	22	43
<i>n</i> -dodecane	5	5	10	71	5	19	24	11
<i>n</i> -tridecane	71	155	338	5	BDL	103	43	108
<i>n</i> -tetradecane	38	61	142	BDL	BDL	83	44	40
<i>n</i> -pentadecane	7	31	45	BDL	BDL	44	20	30
<b>Molecular Weight Ranges</b>								
< C5	3	BDL	4	11	BDL	BDL	BDL	90
C8	78	108	12	BDL	BDL	110	19	584
C6	859	779	307	59	BDL	832	288	2,786
C7	921	404	447	17	BDL	124	46	1,109
C8	418	645	3,774	795	BDL	658	206	2,441
C9	666	1,114	1,842	772	BDL	317	270	778
C14	405	317	471	370	10	204	189	393
C11	344	342	664	307	15	337	305	361
C14	132	174	413	186	8	243	128	132
C11	50	99	220	46	BDL	99	54	74
C14	84	142	304	15	BDL	173	87	78
C15	18	43	61	BDL	BDL	59	32	31
> C15	BDL	9	8	BDL	BDL	12	7	3
TPH	3,978	4,176	8,527	2,578	33	3,168	1,631	8,860

BDL - Below detection limit.



**TABLE 32. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 15 FEET bgs IN JANUARY 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	185	46	ND	BDL	4	215	14	206
<i>n</i> -pentane	360	91	ND	BDL	BDL	94	12	88
2-methylpentane	160	40	ND	7	BDL	30	BDL	26
<i>n</i> -hexane	140	47	ND	BDL	BDL	16	3	5
2,4-dimethylpentane	85	176	ND	35	BDL	133	29	209
benzene	140	252	ND	BDL	13	2,086	165	2,186
<i>n</i> -heptane	70	25	ND	BDL	21	7	BDL	0
toluene	65	5	ND	3	BDL	42	BDL	65
<i>n</i> -octane	40	8	ND	6	BDL	6	3	37
ethylbenzene	705	253	ND	BDL	BDL	208	26	144
<i>p</i> -xylene	2,500	1,134	ND	98	BDL	619	99	959
<i>p</i> -xylene	1,130	523	ND	24	BDL	330	90	142
<i>n</i> -propylbenzene	70	185	ND	17	2	11	4	17
<i>n</i> -decane	20	14	ND	166	98	10	11	4
<i>n</i> -butylbenzene	55	31	ND	12	2	29	16	12
<i>n</i> -dodecane	30	5	ND	61	9	5	19	17
<i>n</i> -tridecane	70	65	ND	9	4	129	29	61
<i>n</i> -tetradecane	20	28	ND	BDL	5	63	26	28
<i>n</i> -pentadecane	8	18	ND	BDL	BDL	18	8	11
<b>Molecular Weight Ranges</b>								
< C5	66	25	ND	4	BDL	45	6	97
C5	683	175	ND	17	3	359	41	474
C6	2,056	710	ND	145	13	2,256	218	2,260
C7	115	396	ND	37	21	300	42	199
C9	4,049	2,246	ND	476	18	1,515	300	1,686
C9	2,863	916	ND	433	2	288	313	659
C10	629	307	ND	162	25	199	179	235
C11	522	320	ND	85	7	275	278	271
C12	143	133	ND	49	2	200	100	94
C13	51	41	ND	9	2	82	48	42
C10	48	77	ND	BDL	BDL	136	49	63
C15	8	17	ND	BDL	BDL	16	7	9
> C15	BDL	3	ND	BDL	BDL	2	2	2
TPH	11,233	5,366	ND	1,417	93	5,673	1,583	6,091

BDL - Below detection limit.

ND - No data because groundwater sampling probe was clogged.

**TABLE 33. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (ppmv) FOR SOIL GAS SAMPLES COLLECTED FROM 2 FEET bgs IN JANUARY 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.29	0.31	ND	0.01	0.01	0.05	0.06	0.02
<i>n</i> -pentane	0.20	0.46	ND	BDL	BDL	BDL	BDL	BDL
2-methylpentane	0.35	0.62	ND	0.06	0.01	0.91	BDL	BDL
<i>n</i> -hexane	0.05	0.27	ND	0.02	BDL	BDL	BDL	BDL
2,4-dimethylpentane	1.41	0.46	ND	0.20	0.07	0.06	0.03	1.21
benzene	0.07	0.13	ND	0.01	0.01	0.04	BDL	0.16
<i>n</i> -heptane	56.13	0.12	ND	0.10	3.77	1.04	2.68	2.66
toluene	61.94	54.01	ND	6.07	4.16	1.03	5.01	2.55
<i>n</i> -octane	5.08	14.40	ND	2.62	0.36	0.93	0.30	0.04
ethylbenzene	1.28	5.06	ND	1.11	0.12	0.38	0.77	0.49
<i>p</i> -xylene	2.61	11.92	ND	2.32	0.20	0.60	1.54	0.07
<i>o</i> -xylene	2.37	8.70	ND	2.10	1.20	0.95	1.57	0.24
<i>n</i> -propylbenzene	0.42	2.00	ND	0.88	0.27	1.81	0.96	0.99
<i>n</i> -decane	0.70	2.24	ND	1.57	1.04	0.91	1.14	0.25
<i>n</i> -butylbenzene	0.62	1.10	ND	0.59	1.64	1.17	1.63	0.12
<i>n</i> -dodecane	0.02	0.46	ND	0.26	0.13	0.57	0.78	0.06
<i>n</i> -tridecane	BDL	0.22	ND	0.06	0.09	0.32	0.42	0.02
<i>n</i> -tetradecane	0.08	0.28	ND	0.12	0.05	0.08	0.16	BDL
<i>n</i> -pentadecane	0.29	0.91	ND	0.52	0.17	0.32	BDL	BDL
<b>Molecular Weight Ranges</b>								
< C5	0.58	0.47	ND	0.17	3.30	0.19	0.19	0.13
C6	0.49	0.60	ND	0.07	0.05	0.05	0.05	0.02
C6	8.13	6.12	ND	2.65	0.45	0.62	0.37	1.34
C9	293.71	256.36	ND	51.78	18.03	8.28	15.26	9.41
C8	144.75	322.47	ND	68.38	16.50	20.63	34.72	10.91
C9	11.02	52.51	ND	38.38	10.35	57.89	22.54	9.16
C10	6.16	37.09	ND	28.43	10.44	49.19	43.98	6.36
C11	0.60	6.47	ND	5.48	13.13	17.56	21.18	2.15
C12	0.07	1.01	ND	1.47	0.73	41.89	6.26	0.34
C11	0.02	0.86	ND	0.82	0.90	4.57	5.43	0.13
C10	0.02	0.08	ND	0.08	0.07	0.13	0.56	BDL
C15	0.02	0.06	ND	0.04	0.02	0.03	BDL	BDL
> C15	BDL	BDL	ND	BDL	BDL	BDL	BDL	BDL
TPH	465.55	684.10	ND	197.76	73.96	201.03	150.53	39.93

BDL - Below detection limit.

ND - No data because water in soil gas probe.

of the well system was in the range of C6 to C11, while on the southern side, the hydrocarbons were mostly in the C7 to C13 range.

The analytical results from the soil gas samples collected from 4 feet bgs are presented in Table 34. Samples were collected from six of the eight probes as MP-4 and MP-6 contained water, making sampling not possible. The hydrocarbon concentrations were slightly higher at 4 feet bgs than they were at the 2-foot depth. The averaged BTEX and TPH concentrations were 34 and 327 ppmv, respectively. The averaged BTEX concentration accounted for just over 10 percent of the TPH, a percentage similar to that observed at the 2-foot depth. The concentrations of BTEX and TPH ranged from 0.04 to 86.3 ppmv and 1.30 to 965.46 ppmv, respectively. The trend of increasing concentrations towards the north was not apparent because of the missing data. The majority of the hydrocarbon in the samples fell in the range between C7 to C11.

#### d. Respiration Testing

The initial data showed that the system was functioning well and that the soils were sufficiently aerated; the O<sub>2</sub> concentrations ranged between 18 and 21 percent at all probe locations except MP-8 at the 2-foot depth where the initial O<sub>2</sub> concentration was 14.5 percent. The CO<sub>2</sub> concentrations correlated well with the O<sub>2</sub> concentrations at all probes.

Periodic soil gas samples were extracted over a 317-hour period while the system remained turned off. The samples were analyzed for O<sub>2</sub> and CO<sub>2</sub> and the data are contained in Appendix B. The data were plotted to form O<sub>2</sub> vs. time curves that also are shown in Appendix B. Oxygen utilization rates were determined by performing linear regression analyses on the zero-order part of the curves. The regression output and a plot illustrating the fit of the resulting lines are included in Appendix B following the field data.

The O<sub>2</sub> utilization rates for each probe location are presented in Table 35. The O<sub>2</sub> utilization rates observed during this test were significantly higher than the rates observed during the shutdown/respiration test conducted in September 1994. Respiration was the highest at MP-7, with rates of 0.0815 and 0.1362 percent/hour for the 2- and 4-foot depths, respectively. Biodegradation rates were calculated on a hexane basis and the results are shown in Table 35. The average calculated rates were 0.9859 and 0.9667 mg-TPH/kg-soil-day for the 2- and 4-foot depths, respectively.

### 3. Shutdown/Respiration Test 3 (21 through 23 June 1995)

#### a. Respiration Testing

The initial soil gas oxygen data indicated that the soil was not receiving adequate airflow from the mKGB system. The oxygen concentrations in soil gas samples from the 2-foot depth were too low (<5 percent) at most locations to conduct an in situ respiration test. The probes at the 4-foot depth were below the water table and could not be

**TABLE 34. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (ppmv) FOR SOIL GAS SAMPLES COLLECTED FROM 4 FEET bgs IN JANUARY 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.04	0.55	0.06	ND	0.26	ND	0.21	ND
<i>n</i> -pentane	BDL	0.88	BDL	ND	BDL	ND	BDL	ND
2-methylpentane	0.03	1.46	0.01	ND	0.01	ND	BDL	ND
<i>n</i> -hexane	BDL	0.75	0.01	ND	BDL	ND	BDL	ND
2,4-dimethylpentane	0.52	1.88	0.06	ND	0.08	ND	BDL	ND
benzene	0.08	0.09	0.01	ND	0.01	ND	0.01	ND
<i>n</i> -heptane	48.48	0.52	0.02	ND	3.75	ND	BDL	ND
toluene	58.47	66.12	7.37	ND	4.06	ND	0.01	ND
<i>n</i> -octane	0.86	17.99	3.50	ND	0.30	ND	0.01	ND
ethylbenzene	1.08	6.12	2.58	ND	0.22	ND	0.01	ND
<i>p</i> -xylene	0.19	2.01	3.65	ND	0.51	ND	BDL	ND
<i>p</i> -xylene	1.04	11.96	3.19	ND	0.49	ND	0.01	ND
<i>n</i> -propylbenzene	2.43	2.23	1.76	ND	0.25	ND	0.01	ND
<i>n</i> -decane	0.65	4.20	1.89	ND	1.10	ND	0.01	ND
<i>n</i> -butylbenzene	0.46	1.17	1.09	ND	1.89	ND	0.01	ND
<i>n</i> -dodecane	0.32	0.61	0.39	ND	0.13	ND	0.01	ND
<i>n</i> -tridecane	0.06	0.16	0.03	ND	0.10	ND	BDL	ND
<i>n</i> -tetradecane	BDL	0.27	0.15	ND	0.05	ND	BDL	ND
<i>n</i> -pentadecane	0.44	2.36	0.57	ND	0.13	ND	0.13	ND
<b>Molecular Weight Ranges</b>								
< C5	0.22	0.19	0.23	ND	0.22	ND	0.22	ND
C6	0.06	1.11	0.04	ND	0.20	ND	0.17	ND
C6	2.79	20.22	0.66	ND	0.47	ND	0.01	ND
C7	164.80	390.26	40.28	ND	17.47	ND	0.03	ND
C6	94.92	406.47	122.12	ND	15.95	ND	0.07	ND
C9	26.93	75.87	74.96	ND	9.12	ND	0.08	ND
C10	20.43	53.43	38.67	ND	11.07	ND	0.21	ND
C11	9.51	13.92	7.97	ND	1.74	ND	0.09	ND
C11	1.74	3.17	2.41	ND	1.02	ND	0.42	ND
C13	0.62	0.59	0.02	ND	1.28	ND	0.01	ND
C14	BDL	0.08	0.04	ND	0.10	ND	BDL	ND
C10	0.03	0.15	0.04	ND	0.01	ND	0.01	ND
> C15	BDL	BDL	BDL	ND	BDL	ND	BDL	ND
TPH	322.05	965.46	287.43	ND	58.67	ND	1.30	ND

BDL - Below detection limit.

ND - No data because water in soil gas sampling probe.

**TABLE 35. O<sub>2</sub> UTILIZATION AND BIODEGRADATION RATES  
CALCULATED FROM O<sub>2</sub> DATA COLLECTED  
DURING THE SECOND IN SITU RESPIRATION TEST**

Monitoring Point ID	2-Foot Depth		4-Foot Depth	
	O <sub>2</sub> Utilization Rate (percent/hr)	Biodegradation Rate (mg/kg/day)	O <sub>2</sub> Utilization Rate (percent/hr)	Biodegradation Rate (mg/kg/day)
1	0.0203	0.3903	0.0079	0.1508
2	0.0342	0.6562	0.0079	0.5892
4	ND	ND	0.0455	0.8740
4	0.0233	0.4465	NA	NA
6	0.0078	0.1495	0.0098	0.1889
6	0.0694	2.2148	0.0542	1.0414
7	0.0815	1.9671	0.1362	2.6149
8	0.0465	1.0695	0.0681	1.3074
Average	0.0403	0.9859	0.0471	0.9667

ND - No data due to probe clogging.

NA - Data not available due to presence of water.

used for collecting soil gas. The compressor line was connected to the 2-foot-deep soil gas probes and air was injected for 24 hours. The oxygen concentrations were increased to near ambient and an in situ respiration test was conducted by extracting soil gas from only the probes 2 feet bgs.

The test lasted 52 hours, during which time a series of soil gas samples were extracted and analyzed for TPH, O<sub>2</sub>, and CO<sub>2</sub>; the data are contained in Appendix C. The O<sub>2</sub> data were plotted vs time and the resulting graphs are presented in Appendix C. O<sub>2</sub> utilization rates were calculated as the slope of the zero-order part of the O<sub>2</sub> vs. time curve. The regression output also is presented in Appendix C.

The O<sub>2</sub> utilization rates calculated for each probe location are presented in Table 36. The rates were the highest among the three respiration tests with an average rate of 0.3738 percent per hour. MP-26 was the most active with an O<sub>2</sub> utilization rate of 0.7038 percent per hour. MP-5 was the least active exhibiting an O<sub>2</sub> utilization rate of 0.0048

**TABLE 36. O<sub>2</sub> UTILIZATION AND BIODEGRADATION RATES  
CALCULATED FROM O<sub>2</sub> DATA COLLECTION  
DURING THE THIRD IN SITU RESPIRATION TEST**

Monitoring Point ID	2-Foot Depth	
	O <sub>2</sub> Utilization Rate (%/hr)	Biodegradation Rate (mg/kg/day)
1	-0.0926 <sup>1</sup>	-1.7779 <sup>1</sup>
2	0.3864	6.1331
4	0.3614	6.8609
4	NA	NA
6	0.7038	0.0928
6	0.7038	12.8239
7	0.4732	9.5036
8	0.3134	6.6646
Average	0.3738	7.0132

NA - Data not available due to presence of water.

<sup>1</sup> Data not included in average due to increased O<sub>2</sub> concentration after shutdown.

percent per hour. The O<sub>2</sub> level at MP-1 increased over the duration of the test, so the data from this point were excluded from the analyses.

The O<sub>2</sub> utilization rates were used to calculate biodegradation rates using the method described by Hincsee (Hincsee et al., 1992). The resulting values are included in Table 36. The average biodegradation rate was just over 7 mg/kg/day, a rate over seven times greater than that observed in January.

#### **D. FINAL SITE CHARACTERIZATION**

##### **1. Soil JP-4 Concentrations**

After 12 months of operation, the modified KGB well system was turned off and a final set of soil samples was collected for analyses. The samples were pulled from depths corresponding to the initial sample set so that the concentrations of the initial and final

samples could be compared. The final soil samples were collected from 4, 8, and 12 feet bgs, approximately 1 foot from the points where the original samples were collected. The samples were analyzed for the 19 hydrocarbon compounds that comprise the JP-4 fingerprint. The results are presented in Tables 37, 38, and 39.

Table 37 contains the data for the final set of soils collected from 4 feet bgs. These soils were characterized with average BTEX and TPH concentrations of 8.66 and 107.6 mg/kg, respectively. The averaged BTEX concentration accounted for approximately 8.1 percent of the averaged TPH concentration. The concentrations ranged from 0.03 to 35.35 mg/kg for BTEX and TPH, respectively. Soils from MP-1 showed the lowest hydrocarbon concentrations, and MP-8 had the highest levels. The molecular weight data showed that the majority of the hydrocarbon was in the C7 to C12 range with some heavier hydrocarbon present in the samples from MP-6 and MP-7.

The data from the soils collected from the 8-foot depth are presented in Table 38. On average, the soils from this depth contained lower hydrocarbon levels than the soils from the 4-foot depth. The average BTEX and TPH concentrations were 6.42 and 59.73 mg/kg, respectively. The averaged BTEX concentration accounted for approximately 10.8 percent of the averaged TPH concentration. The majority of the hydrocarbons fell in the range between C7 to C12, with some heavier hydrocarbons in the higher molecular weight ranges at MP-3, MP-5, MP-6, and MP-8.

Soil samples from the 12-foot depth were collected from seven of the eight locations and the analytical results are shown in Table 39. A natural gas line ran adjacent to MP-5, making sampling at that location impossible. The BTEX and TPH concentrations in soils from 12 feet bgs contained the least amount of hydrocarbon among the three depths sampled. The average BTEX and TPH concentrations were 5.43 and 88.24 mg/kg, respectively. On average, the BTEX accounted for approximately 6.2 percent of the TPH. The concentrations ranged from 0.10 to 24.18 mg/kg and from 3.51 to 449.68 mg/kg for BTEX and TPH, respectively. There was no distinct pattern in the spatial distribution of the hydrocarbon contamination at this depth. The molecular weight data showed that the majority of the hydrocarbon fell in the range between C7 and C13 when the TPH concentration was above 100 mg/kg, and no general trend in molecular weight distribution was obvious at the lower concentrations.

## **2. Groundwater JP-4 Concentrations**

Groundwater samples were collected in June 1995, prior to turning off the modified KGB well system. Samples were collected from the four depths as in all previous sampling events, and also at the 4-foot depth from which soil gas samples had been collected previously. The groundwater elevation had risen to approximately 3 feet bgs due to heavy rains from a hurricane that hit the Florida panhandle within 1 week of the final sampling event. Because it was not possible to collect soil gas samples from this depth, and because the probes at the 4-foot depth were below the water table, it was decided to collect groundwater samples from these probes. The results from these analyses are presented

TABLE 37. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (mg/kg) FOR SOIL SAMPLES COLLECTED FROM 4 FEET bgs IN JUNE 1995

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	0.11	BDL	BDL	BDL	0.17	0.54	BDL
<i>n</i> -pentane	BDL	0.64	BDL	BDL	BDL	0.06	0.54	0.05
2-methylpentane	BDL	BDL	BDL	BDL	BDL	0.17	0.61	0.18
<i>n</i> -hexane	BDL	BDL	0.15	BDL	BDL	0.18	0.50	0.20
2,4-dimethylpentane	BDL	BDL	BDL	BDL	BDL	0.36	1.32	0.17
benzene	BDL	BDL	BDL	BDL	BDL	0.04	0.18	BDL
<i>n</i> -heptane	0.01	BDL	BDL	BDL	0.01	0.06	0.06	2.55
toluene	0.01	1.37	0.05	0.01	0.04	0.05	0.98	3.64
<i>n</i> -octane	0.01	2.72	0.02	BDL	0.10	0.06	0.02	15.24
ethylbenzene	0.01	6.74	0.08	BDL	0.06	0.07	1.38	6.30
<i>p</i> -xylene	0.01	3.60	BDL	0.02	0.04	1.76	4.06	7.27
<i>o</i> -xylene	BDL	9.21	0.06	0.01	0.11	0.76	3.21	18.14
<i>n</i> -propylbenzene	BDL	4.89	0.05	BDL	0.09	0.27	0.06	18.94
<i>n</i> -decane	0.01	14.05	0.06	0.02	0.10	0.10	0.06	35.02
<i>n</i> -butylbenzene	0.01	9.63	0.08	0.02	0.26	0.09	0.02	10.49
<i>n</i> -dodecane	0.01	BDL	0.05	0.02	1.06	0.14	0.13	BDL
<i>n</i> -tridecane	0.04	0.08	0.17	0.01	0.16	0.14	0.12	0.28
<i>n</i> -tetradecane	0.04	0.58	0.31	BDL	0.04	3.47	1.39	0.58
<i>n</i> -pentadecane	BDL	0.51	0.06	0.01	BDL	2.39	1.58	0.09
Molecular Weight Ranges								
< C5	BDL	BDL	BDL	BDL	BDL	BDL	0.02	0.02
C5	BDL	0.37	BDL	BDL	BDL	0.08	0.45	0.03
C6	BDL	0.10	0.15	BDL	0.06	0.73	2.69	0.59
C7	0.02	6.18	0.13	0.01	0.12	1.78	5.18	35.99
C8	0.02	72.46	0.45	0.04	0.89	3.89	8.65	148.97
C9	0.01	44.95	0.20	0.04	0.65	1.24	0.64	122.52
C10	0.03	131.18	0.41	0.12	1.33	1.48	1.04	186.53
C11	0.01	22.42	0.15	0.04	1.69	0.30	0.46	21.55
C12	0.01	0.70	0.20	0.04	2.54	0.65	0.43	0.62
C13	BDL	0.10	0.45	0.02	0.53	0.50	0.26	0.46
C14	0.02	1.21	0.79	0.01	0.14	7.01	2.40	0.59
C15	0.02	0.76	0.06	0.01	0.02	5.18	2.88	0.10
> C15	BDL	0.58	0.05	0.04	0.05	1.60	0.61	0.17
TPH	0.14	281.07	3.05	0.37	7.97	24.45	25.72	518.15

BDL - Below detection limit.



**TABLE 38. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (mg/kg) FOR SOIL SAMPLES COLLECTED FROM 8 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	BDL	BDL	0.17	BDL	BDL	4.02
<i>n</i> -pentane	0.02	BDL	0.04	BDL	0.06	BDL	BDL	3.11
2-methylpentane	0.01	0.05	0.07	BDL	0.17	BDL	BDL	2.83
<i>n</i> -hexane	0.02	0.03	0.03	BDL	0.18	BDL	BDL	2.10
2,4-dimethylpentane	0.02	0.05	BDL	BDL	0.36	BDL	BDL	5.06
benzene	BDL	BDL	BDL	BDL	0.04	0.04	0.04	1.54
<i>n</i> -heptane	0.08	0.28	0.18	BDL	0.06	BDL	BDL	2.85
toluene	0.02	2.42	0.08	0.01	0.05	0.03	0.02	3.00
<i>n</i> -octane	0.02	1.08	0.28	0.01	0.06	0.02	BDL	7.40
ethylbenzene	0.03	3.29	0.18	BDL	0.07	BDL	BDL	7.78
<i>o</i> -xylene	0.03	2.92	0.26	0.01	1.76	0.04	BDL	16.10
<i>o</i> -xylene	0.02	1.52	0.18	0.01	0.76	0.06	BDL	9.01
<i>n</i> -propylbenzene	0.04	1.74	0.13	0.03	0.27	0.35	0.03	9.03
<i>n</i> -decane	0.16	4.86	0.48	0.02	0.13	0.08	0.02	27.98
<i>n</i> -butylbenzene	0.04	5.01	0.23	BDL	0.09	BDL	BDL	24.63
<i>n</i> -dodecane	0.07	1.38	0.39	0.03	0.14	0.06	0.06	BDL
<i>n</i> -tridecane	0.06	BDL	0.76	0.05	0.14	0.16	0.07	1.85
<i>n</i> -tetradecane	0.03	0.04	1.12	0.03	3.47	0.52	0.38	4.54
<i>n</i> -pentadecane	BDL	0.10	1.02	0.02	2.39	0.79	0.32	2.32
<b>Molecular Weight Ranges</b>								
< C5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.10
C5	0.01	BDL	0.02	BDL	0.08	BDL	BDL	2.84
C6	0.05	0.61	0.03	BDL	0.73	0.04	0.04	11.43
C7	0.37	10.24	1.30	0.03	1.78	0.13	0.05	35.03
C8	0.96	32.85	2.83	0.13	3.89	0.55	0.14	105.58
C9	0.38	18.65	1.22	0.05	1.24	0.83	0.10	74.25
C10	0.65	47.54	1.61	0.20	1.48	0.48	0.15	16.04
C11	0.29	18.67	0.76	0.09	0.30	0.12	0.05	30.33
C11	0.27	3.37	1.09	0.09	0.05	0.19	0.14	2.33
C13	0.19	BDL	1.49	0.08	0.50	0.25	0.08	2.59
C14	0.12	0.03	2.43	0.06	7.01	1.17	0.34	9.54
C15	0.04	0.12	1.71	0.02	5.18	1.29	0.45	4.16
> C15	0.02	0.12	0.22	0.02	1.60	0.43	0.23	0.91
TPH	3.35	132.20	14.72	0.73	24.45	5.48	1.77	295.14

BDL - Below detection limit.

**TABLE 39. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (mg/kg) FOR SOIL SAMPLES COLLECTED FROM 12 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.48	0.36	0.46	BDL	ND	BDL	BDL	0.07
<i>n</i> -pentane	0.30	0.18	0.40	BDL	ND	0.05	BDL	BDL
2-methylpentane	0.24	0.12	0.50	BDL	ND	0.19	BDL	0.02
<i>n</i> -hexane	0.17	0.09	0.44	BDL	ND	0.32	BDL	0.01
2,4-dimethylpentane	0.27	0.13	0.59	BDL	ND	0.58	BDL	0.03
benzene	0.67	0.6	0.18	BDL	ND	BDL	0.05	0.10
<i>n</i> -heptane	0.07	0.9	0.12	BDL	ND	0.94	BDL	BDL
toluene	0.04	0.6	0.09	1.63	ND	0.35	0.01	0.02
<i>n</i> -octane	0.09	0.25	0.06	2.61	ND	0.98	0.01	0.01
ethylbenzene	0.09	0.37	0.30	4.82	ND	1.83	0.02	0.06
<i>p</i> -xylene	0.38	0.55	0.89	9.25	ND	3.58	0.01	0.06
<i>o</i> -xylene	0.18	0.34	0.39	8.48	ND	3.12	0.01	0.02
<i>n</i> -propylbenzene	0.03	0.39	0.07	4.02	ND	3.64	0.03	0.20
<i>n</i> -decane	0.10	0.39	0.08	23.23	ND	12.81	0.09	0.06
<i>n</i> -butylbenzene	0.01	0.41	0.08	13.02	ND	9.38	0.01	BDL
<i>n</i> -dodecane	0.03	0.34	0.10	17.28	ND	0.03	0.02	0.23
<i>n</i> -tridecane	0.02	0.51	0.07	8.72	ND	0.12	0.01	0.29
<i>n</i> -tetradecane	BDL	1.24	0.20	BDL	ND	0.10	0.07	2.57
<i>n</i> -pentadecane	0.02	0.39	0.07	0.13	ND	0.79	0.06	1.26
<b>Molecular Weight Ranges</b>								
< C5	0.03	0.01	BDL	BDL	ND	BDL	BDL	BDL
C5	0.30	0.20	0.35	BDL	ND	0.03	0.03	0.02
C6	1.34	0.39	1.74	0.36	ND	1.07	0.18	0.14
C7	0.78	1.24	2.02	8.34	ND	9.07	0.02	0.10
C8	1.20	3.52	2.09	104.68	ND	3.77	0.18	0.41
C9	0.30	1.56	0.83	55.93	ND	27.88	0.17	0.26
C10	0.38	2.86	1.83	14.70	ND	66.52	0.17	0.30
C11	0.06	1.05	0.51	129.72	ND	5.72	0.07	0.22
C12	0.07	3.45	0.82	118.30	ND	0.03	0.15	0.45
C13	0.02	5.00	0.98	15.48	ND	0.04	0.26	0.45
C14	BDL	4.61	0.44	0.06	ND	0.13	0.87	2.70
C15	0.01	1.20	0.13	0.26	ND	0.12	1.11	2.41
> C15	BDL	0.13	0.09	1.55	ND	0.09	0.36	1.00
TPH	4.48	25.22	11.84	449.68	ND	114.47	3.51	8.46

BDL - Below detection limit.

ND - No data because of gas line interference.

below; however, there are no other data to directly compare against the results from the June 1995 samples.

The groundwater samples were analyzed for the 19 specific compounds that comprise the JP-4 fingerprint, for molecular weight ranges based on the number of carbon atoms, and for TPH. The results from these analyses are presented in Tables 40, 41, 42, 43, and 44. The original data are contained in the Data Package dated June 1995.

Groundwater samples were retrieved from six of the eight locations at the 4-foot depth; the resulting hydrocarbon data for these samples are presented in Table 40. The averaged concentrations of BTEX and TPH were 44 and 1,556  $\mu\text{g/L}$ , respectively. On average, the BTEX accounted for less than 3 percent of the TPH. The concentrations ranged between 12 and 127  $\mu\text{g/L}$  and 201 and 4,775  $\mu\text{g/L}$  for BTEX and TPH, respectively. The TPH data showed that the groundwater on the southern side of the well system was significantly more contaminated than the groundwater on the northern side. Groundwater from MP-5 contained the lowest concentrations of both BTEX and TPH, whereas groundwater from MP-6 contained the highest concentrations. The molecular weight data did not show any clear trend in hydrocarbon distribution.

The analytical data from the groundwater samples collected from 6 feet bgs are presented in Table 41. BTEX and TPH concentrations ranged from 2 to 2,486  $\mu\text{g/L}$  and from 451 to 13,964  $\mu\text{g/L}$ , respectively. MP-5 was characterized as having the lowest, and MP-2 with the highest, BTEX and TPH concentrations. The averaged concentrations were 614 and 5,239  $\mu\text{g/L}$  for BTEX and TPH, respectively. The average BTEX concentration accounted for 11.7 percent of the average TPH concentration. Although the hydrocarbons covered the entire molecular weight range from <C5 to >C15, the majority fell in the range between C6 to C14.

Table 42 contains the analytical results from the groundwater samples pulled from 9 feet bgs at all eight monitoring point locations. The data show that the BTEX and TPH concentrations ranged from below detection to 2,533  $\mu\text{g/L}$  and from 314 to 14,403  $\mu\text{g/L}$ , respectively. MP-5 was characterized with the lowest BTEX concentrations, and MP-1 showed the lowest TPH levels. MP-2 contained the highest concentrations of both BTEX and TPH. The averaged concentrations of BTEX and TPH were 543 and 4,902  $\mu\text{g/L}$ , respectively. Approximately 11.1 percent of the average TPH concentration was accounted for by the average BTEX concentration. The molecular weight data indicated that the hydrocarbon covered the entire molecular weight range. The hydrocarbons on the northern side of the system appeared to be slightly lighter than the hydrocarbons on the southern side.

Groundwater samples were collected from all eight locations at the 12-foot depth; the results from the GC analyses are presented in Table 43. The data show that the hydrocarbon levels at this depth were higher than at the shallower depths, with the BTEX and TPH concentrations ranging from 2 to 3,349  $\mu\text{g/L}$  and from 114 to 15,159  $\mu\text{g/L}$ , respectively. MP-8 contained the highest, and MP-5 the lowest, levels of both BTEX and TPH. The averaged BTEX and TPH concentrations were 1,285 and 6,690  $\mu\text{g/L}$ ,

**TABLE 40. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 4 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	ND	ND	BDL	BDL	BDL	BDL	BDL
<i>n</i> -pentane	BDL	ND	ND	BDL	BDL	BDL	BDL	BDL
2-methylpentane	BDL	ND	ND	BDL	BDL	BDL	BDL	BDL
<i>n</i> -hexane	BDL	ND	ND	BDL	BDL	BDL	BDL	BDL
2,4-dimethylpentane	BDL	ND	ND	12	BDL	20	15	36
benzene	3	ND	ND	BDL	BDL	BDL	BDL	BDL
<i>n</i> -heptane	4	ND	ND	12	BDL	BDL	BDL	BDL
toluene	3	ND	ND	4	2	5	BDL	BDL
<i>n</i> -octane	5	ND	ND	13	BDL	6	BDL	2
ethylbenzene	4	ND	ND	4	3	37	4	7
<i>p</i> -xylene	6	ND	ND	7	3	69	12	16
<i>o</i> -xylene	7	ND	ND	6	3	16	13	27
<i>n</i> -propylbenzene	9	ND	ND	3	2	13	6	4
<i>n</i> -decane	16	ND	ND	14	4	9	4	19
<i>n</i> -butylbenzene	5	ND	ND	2	2	44	26	11
<i>n</i> -dodecane	10	ND	ND	18	BDL	13	5	36
<i>n</i> -tridecane	9	ND	ND	14	7	188	5	25
<i>n</i> -tetradecane	8	ND	ND	15	BDL	106	36	19
<i>n</i> -pentadecane	9	ND	ND	13	BDL	27	3	8
<b>Molecular Weight Ranges</b>								
< C5	BDL	ND	ND	BDL	BDL	BDL	4	BDL
C5	30	ND	ND	27	BDL	BDL	24	29
C6	5	ND	ND	34	115	45	15	36
C7	45	ND	ND	34	4	161	10	97
C8	272	ND	ND	60	20	447	62	196
C9	72	ND	ND	148	5	383	90	142
C10	150	ND	ND	46	10	1,043	290	407
C11	68	ND	ND	5	BDL	639	210	385
C11	36	ND	ND	27	14	498	74	308
C11	12	ND	ND	21	10	716	73	270
C10	12	ND	ND	22	8	622	214	100
C15	12	ND	ND	18	9	135	74	26
> C15	BDL	ND	ND	BDL	BDL	66	53	12
TPH	714	ND	ND	442	201	4,775	1,193	2,008

BDL - Below detection limit.

ND - No data due to probe clogging.

**TABLE 41. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 6 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	49	BDL	BDL	BDL	77	BDL
<i>n</i> -pentane	BDL	BDL	BDL	BDL	BDL	BDL	11	BDL
2-methylpentane	BDL	9	BDL	BDL	BDL	BDL	7	BDL
<i>n</i> -hexane	BDL	6	BDL	BDL	BDL	BDL	4	BDL
2,4-dimethylpentane	BDL	111	85	BDL	BDL	25	57	43
benzene	10	8	BDL	BDL	BDL	BDL	15	BDL
<i>n</i> -heptane	13	21	BDL	BDL	BDL	BDL	BDL	BDL
toluene	7	17	16	2	BDL	7	8	6
<i>n</i> -octane	12	28	16	5	BDL	9	5	4
ethylbenzene	8	229	121	66	BDL	64	59	25
<i>p</i> -xylene	20	1,606	587	412	2	63	98	127
<i>o</i> -xylene	25	625	402	101	BDL	16	58	99
<i>n</i> -propylbenzene	10	25	7	19	4	20	5	5
<i>n</i> -decane	44	73	16	12	3	13	9	5
<i>n</i> -butylbenzene	12	32	24	20	6	46	37	13
<i>n</i> -dodecane	32	42	6	4	8	3	12	21
<i>n</i> -tridecane	7	145	230	39	11	239	102	94
<i>n</i> -tetradecane	6	61	90	4	5	143	74	42
<i>n</i> -pentadecane	6	BDL	19	3	3	27	26	20
<b>Molecular Weight Ranges</b>								
< C5	6	BDL	4	BDL	BDL	BDL	16	BDL
C5	45	7	27	8	65	BDL	59	8
C5	16	230	141	66	BDL	57	110	56
C8	145	775	606	96	BDL	203	201	299
C8	774	6,505	2,513	1,292	8	541	505	571
C8	329	1,891	1,180	635	16	381	495	260
C10	354	22,151	1,432	1,299	106	1,076	957	498
C11	272	742	393	250	128	564	477	280
C12	161	539	394	356	52	444	356	226
C11	115	571	898	138	33	942	472	424
C14	50	369	606	35	39	831	457	284
C15	23	77	115	4	4	155	19	79
> C15	5	43	76	BDL	BDL	109	74	31
TPH	2,293	13,964	8,385	4,179	451	5,303	4,318	3,016

BDL - Below detection limit.

**TABLE 42. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 9 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	BDL	BDL	BDL	32	BDL	BDL
<i>n</i> -pentane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
2-methylpentane	BDL	38	BDL	BDL	BDL	BDL	BDL	BDL
<i>n</i> -hexane	BDL	83	47	BDL	BDL	BDL	12	5
2,4-dimethylpentane	BDL	497	144	BDL	BDL	28	71	34
benzene	BDL	29	326	BDL	BDL	BDL	4	BDL
<i>n</i> -heptane	BDL	17	12	BDL	BDL	8	BDL	9
toluene	BDL	97	18	4	BDL	6	11	8
<i>n</i> -octane	13	16	11	9	BDL	22	3	15
ethylbenzene	3	314	87	26	BDL	86	50	29
<i>p</i> -xylene	3	1,555	207	302	BDL	96	131	124
<i>o</i> -xylene	4	538	51	122	BDL	10	87	17
<i>n</i> -propylbenzene	5	37	16	32	BDL	28	6	10
<i>n</i> -decane	11	24	286	17	4	30	8	12
<i>n</i> -butylbenzene	9	37	27	27	2	53	28	28
<i>n</i> -dodecane	3	15	3	3	6	27	3	30
<i>n</i> -tridecane	6	111	133	44	13	221	91	131
<i>n</i> -tetradecane	3	42	50	8	12	137	70	53
<i>n</i> -pentadecane	3	16	15	BDL	6	7	21	34
<b>Molecular Weight Ranges</b>								
< C5	BDL	19	14	BDL	BDL	BDL	15	BDL
C5	50	408	171	4	BDL	12	131	94
C5	48	1,042	982	73	BDL	38	171	94
C7	9	1,986	1,033	167	BDL	229	210	410
C8	73	5,471	961	1,066	BDL	596	612	425
C9	13	1,814	758	597	5	483	384	333
C10	75	2,142	1,025	1,267	85	1,114	736	687
C11	10	377	295	251	34	625	356	380
C12	4	328	312	332	391	651	170	341
C13	15	426	557	164	32	858	430	566
C14	13	285	335	52	92	707	465	354
C15	4	75	55	BDL	21	239	109	130
> C15	BDL	30	28	BDL	BDL	82	58	41
TPH	314	14,403	6,526	3,973	660	5,634	3,847	3,855

BDL - Below detection limit.

**TABLE 43. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 12 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	1,081
<i>n</i> -pentane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
2-methylpentane	BDL	208	20	29	BDL	87	75	137
<i>n</i> -hexane	122	93	21	BDL	BDL	BDL	4	46
2,4-dimethylpentane	27	168	148	112	BDL	162	144	556
benzene	BDL	8	47	418	BDL	686	1,905	2,025
<i>n</i> -heptane	35	7	11	BDL	BDL	BDL	BDL	28
toluene	11	11	27	13	BDL	38	23	4
<i>n</i> -octane	34	18	20	8	BDL	BDL	20	16
ethylbenzene	12	8	298	37	BDL	124	114	155
<i>p</i> -xylene	5	18	1,200	245	2	428	310	1,016
<i>o</i> -xylene	11	9	527	21	BDL	193	181	149
<i>n</i> -propylbenzene	5	16	16	12	BDL	7	4	9
<i>n</i> -decane	28	28	29	7	2	9	11	18
<i>n</i> -butylbenzene	45	37	20	16	BDL	9	11	48
<i>n</i> -dodecane	15	12	11	3	5	10	7	16
<i>n</i> -tridecane	3	115	220	54	5	16	27	100
<i>n</i> -tetradecane	24	39	85	31	5	13	14	15
<i>n</i> -pentadecane	3	15	14	4	4	21	21	33
<b>Molecular Weight Ranges</b>								
< C5	BDL	BDL	BDL	21	BDL	32	105	141
C5	127	133	66	166	BDL	210	412	803
C6	714	964	378	895	16	1,445	3,459	4,680
C7	1,837	1,552	1,189	394	BDL	481	419	2361
C8	627	382	5,097	815	5	1,672	1,568	3,657
C9	139	443	1,107	296	4	220	229	791
C12	710	854	1,749	524	37	340	332	1,277
C13	275	302	411	173	BDL	61	179	435
C12	108	92	484	162	8	67	119	332
C13	74	465	892	224	16	52	129	368
C12	152	263	539	200	22	77	98	155
C15	9	75	124	24	6	68	87	100
> C15	4	30	73	4	BDL	14	37	51
TPH	4,776	5,555	12,109	3,898	114	4,739	7,173	15,159

BDL - Below detection limit.

respectively. On average, 19.2 percent of the TPH was accounted for as BTEX. The hydrocarbon composition covered the molecular weight range, with a larger fraction being contained in the C5 to C13 range.

The hydrocarbon data from the groundwater samples from all eight locations at the 15-foot depth are contained in Table 44. The data show that, on average, this depth contained the highest levels of both BTEX and TPH. The concentrations ranged from 61 to 3,543  $\mu\text{g/L}$  and from 274 to 19,075  $\mu\text{g/L}$  for BTEX and TPH, respectively. MP-1 was characterized with the highest, and MP-5 with the lowest, BTEX and TPH concentrations. The average concentrations were 1,668 and 7,365  $\mu\text{g/L}$  for BTEX and TPH, respectively. The average BTEX concentration accounted for approximately 22.7 percent of the average TPH concentration. The bulk of the hydrocarbon was in the C5 to C14 range, with a large percentage falling in the lower-molecular-weight (C5 to C10) range.

### 3. Soil Gas JP-4 Concentrations

During the final shutdown/respiration test, at which time the final set of soil gas samples were pulled for GC analyses, the groundwater elevation was at approximately 3½ feet bgs due to heavy rains resulting from a hurricane that hit the Florida panhandle. Thus, soil gas samples could not be retrieved from the probes at the 4-foot depth. Because gas sampling was not possible, groundwater samples were collected from the 4-foot depth and the results from those analyses are discussed in Section II.D.2. The analytical results for the soil gas from the 2-foot depth are presented in Table 45.

The soil gas probe at the 2-foot depth in MP-4 contained water; thus, sampling from this probe was not possible. The data from the seven probes that were sampled show that the BTEX and TPH concentrations ranged from 0.06 to 81.99 ppmv and from 1.84 to 677.92 ppmv, respectively. MP-5 was characterized with the lowest BTEX and TPH concentration and MP-2 with the highest. The averaged concentrations were 12.85 and 136.46 ppmv, respectively. The average BTEX concentration accounted for slightly less than 9.5 percent of the average TPH concentration. Benzene concentrations were consistently low, averaging less than 0.02 ppmv. The molecular weight data showed that the hydrocarbons on the north side of the well system fell in the range between C7 to C13 and the hydrocarbons on the south side ranged between C7 and C14.



**TABLE 44. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA ( $\mu\text{g/L}$ ) FOR GROUNDWATER SAMPLES COLLECTED FROM 15 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	560	234	BDL	BDL	27	BDL	BDL	659
<i>n</i> -pentane	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
2-methylpentane	168	64	BDL	29	8	43	44	64
<i>n</i> -hexane	137	50	BDL	BDL	BDL	BDL	BDL	13
2,4-dimethylpentane	750	229	32	112	BDL	129	123	279
benzene	100	264	BDL	418	61	958	2,173	1,800
<i>n</i> -heptane	36	22	13	BDL	BDL	9	BDL	BDL
toluene	2	11	4	13	BDL	4	10	29
<i>n</i> -octane	26	14	11	8	BDL	11	25	35
ethylbenzene	570	327	6	37	BDL	64	49	61
<i>o</i> -xylene	2,209	1,269	40	245	BDL	171	110	803
<i>o</i> -xylene	662	587	78	21	BDL	84	90	17
<i>n</i> -propylbenzene	63	20	35	12	2	8	9	10
<i>n</i> -decane	26	14	4	7	3	5	11	6
<i>n</i> -butylbenzene	52	58	23	16	2	11	18	21
<i>n</i> -dodecane	30	14	6	3	2	4	3	12
<i>n</i> -tridecane	61	43	102	54	BDL	27	29	46
<i>n</i> -tetradecane	20	17	47	31	5	38	13	18
<i>n</i> -pentadecane	BDL	9	3	4	BDL	6	12	5
<b>Molecular Weight Ranges</b>								
< C5	22	15	BDL	21	BDL	40	108	60
C5	757	192	44	166	16	245	238	409
C5	2,136	1,016	32	895	112	1,953	3,833	3,531
C9	2,578	1,132	85	394	8	635	397	833
C5	7,381	4,860	347	815	16	930	847	2,513
C9	2,187	997	473	296	6	189	374	543
C10	2,666	1,324	740	524	68	324	524	846
C11	432	249	324	173	18	137	213	255
C12	512	201	188	162	10	110	110	199
C13	277	192	337	224	10	133	155	190
C10	124	131	357	200	8	211	888	123
C15	BDL	32	71	24	BDL	46	38	17
> C15	BDL	20	60	4	BDL	22	12	10
TPH	19,075	10,361	3,058	3,898	274	4,975	7,746	9,529

BDL - Below detection limit.

**TABLE 45. SPECIFIC-COMPOUND (JP-4), MOLECULAR WEIGHT RANGE, AND TPH DATA (ppmv) FOR SOIL GAS SAMPLES COLLECTED FROM 2 FEET bgs IN JUNE 1995**

Compound	MP-1	MP-2	MP-3	MP-4	MP-5	MP-6	MP-7	MP-8
Isopentane	0.01	0.72	BDL	ND	0.01	0.01	4.12	0.01
<i>n</i> -pentane	BDL	0.65	BDL	ND	0.01	BDL	1.51	BDL
2-methylpentane	BDL	0.04	BDL	ND	BDL	BDL	0.53	0.01
<i>n</i> -hexane	BDL	BDL	BDL	ND	BDL	BDL	0.30	BDL
2,4-dimethylpentane	BDL	0.06	0.01	ND	BDL	BDL	0.11	0.03
benzene	0.02	0.02	BDL	ND	0.02	0.01	0.02	0.04
<i>n</i> -heptane	0.01	5.35	BDL	ND	0.01	0.26	0.03	0.90
toluene	0.04	29.56	0.34	ND	0.02	0.39	0.05	1.36
<i>n</i> -octane	0.02	7.27	0.01	ND	BDL	0.08	0.01	0.16
ethylbenzene	0.01	8.91	0.03	ND	BDL	0.04	0.04	0.64
<i>p</i> -xylene	0.04	22.47	0.09	ND	0.01	0.06	0.01	0.04
<i>o</i> -xylene	0.04	21.03	0.12	ND	0.01	0.09	0.06	4.32
<i>n</i> -propylbenzene	0.02	5.34	0.08	ND	0.01	0.16	0.04	2.17
<i>n</i> -decane	0.03	6.84	0.24	ND	0.02	0.30	0.05	1.29
<i>n</i> -butylbenzene	0.01	12.46	0.06	ND	0.02	0.41	0.09	2.50
<i>n</i> -dodecane	0.03	1.87	0.06	ND	0.02	0.86	0.02	2.57
<i>n</i> -tridecane	0.04	0.56	0.04	ND	0.06	1.46	0.06	1.59
<i>n</i> -tetradecane	0.12	0.18	0.06	ND	0.19	1.92	0.19	4.09
<i>n</i> -pentadecane	1.01	BDL	0.02	ND	BDL	0.50	0.13	0.51
<b>Molecular Weight Ranges</b>								
< C5	0.07	0.28	0.05	ND	0.10	0.05	1.11	0.17
C8	0.01	1.09	0.02	ND	0.02	0.01	4.67	0.02
C6	0.04	0.49	0.06	ND	0.06	0.07	1.91	0.41
C7	0.14	73.92	0.75	ND	0.07	0.94	0.51	4.48
C8	0.50	307.71	1.24	ND	0.11	1.48	0.39	20.08
C9	0.33	132.20	1.52	ND	0.11	2.99	0.04	33.87
C14	0.47	113.15	25.51	ND	0.20	8.32	2.44	52.70
C14	0.19	30.76	0.92	ND	0.16	9.03	1.53	33.62
C12	0.10	11.19	0.32	ND	0.11	6.21	0.46	15.43
C13	0.17	7.00	0.43	ND	0.25	12.07	0.38	17.48
C14	0.11	0.10	0.07	ND	0.14	3.58	0.23	3.87
C15	0.21	0.04	0.00	ND	0.10	0.31	0.01	0.70
> C15	0.22	BDL	0.00	ND	0.35	BDL	BDL	0.01
TPH	2.35	677.92	30.89	ND	1.84	45.07	14.29	182.86

BDL - Below detection limit.

ND - No data because water in soil gas probe.

## **SECTION IV DISCUSSION**

### **A. IN-WELL AIR STRIPPING COMPONENT**

Two well system configurations were included in this study to determine the effectiveness of an existing system design and to determine if the principles of the conventional air lift pump design could be incorporated into a more standard bioventing injection vent well design. The plan was to run each of the well systems separately for 2- to 3-month periods. Each system would be evaluated to determine its ability to remediate contamination below the water table and to support bioventing for remediation of contamination above the water table and destruction of contaminants in the system off-gas.

The commercially available design was a modification to the KGB system currently marketed by IEG Technologies, Corporation, out of Charlotte, North Carolina. The conventional KGB system uses forced air to facilitate groundwater circulation and stripping of volatile contaminants from groundwater. The KGB design incorporates vapor extraction to remove residual volatile contaminants from the vadose zone, as well as volatile contaminants from the air stripper off-gas. The modification used in this study included the removal of the vapor extraction portion of the KGB, and incorporation of direct injection of vapor and residual oxygen into the vadose zone for biodegradation (bioventing).

The modified bioventing well (MBW) was based on a design Battelle submitted to the Air Force in 1990 (Hinchee, 1990). The design incorporated a conventional air lift pump design commonly used for dewatering into a 4-inch-diameter bioventing air injection vent well. The vent well was modified to include an upper and a lower screen section. The system was designed so that the air lift pump facilitated groundwater circulation and air stripping, and the off-gas from the system supported bioventing of the residual contamination in the vadose zone as well as the contaminants in the off-gas.

In-well air stripping systems have the potential to remediate hydrocarbon contamination below the water table via two distinct mechanisms. The introduction of air into the water column reduces the specific gravity of the fluid in the well. The water outside of the well, being of normal weight, forces the fluid in the well to rise, thus causing the air lift to function (Powers, 1992; Krebs, 1995). The air lift pump draws contaminated groundwater into the well through the lower screen at the bottom of the well. As the water rises in the well, volatile contaminants are transferred from the aqueous phase to the gas phase (air stripping). This mechanism is a phase-transfer mechanism for remediating the water, but does not provide for contaminant destruction. The second potential mechanism for remediation is biodegradation. During air lift, the water entering the well with low levels of DO is oxygenated through the transfer of oxygen from the injected air. The oxygenated water is circulated in the aquifer, thus delivering oxygen to the microbes. Hydrocarbons are degraded primarily aerobically, and biodegradation in the saturated zone can proceed when the indigenous microorganisms are provided sufficient oxygen.

The mKGB well was turned on first; however, the air distributor was disconnected and the system was not supporting the air lift. The decision was made to turn on the MBW system and run it for the first 3-month period and to repair the mKGB system in the meantime.

The operation of the MBW system could not be optimized for either water pumping or air stripping efficiency because the shallow vadose zone would not support the off-gas loading. The maximum air flow rate that could be injected into the well without emitting excess vapor from the soil surface was 1.0 cubic foot per minute (cfm). Even though the operation was not optimized, the study provided valuable data on the principles of well system operation.

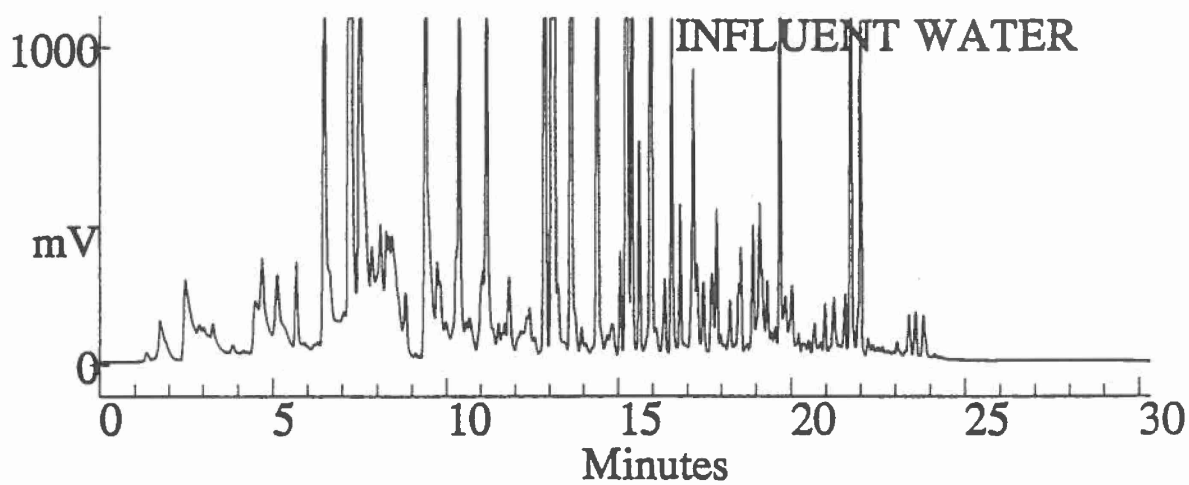
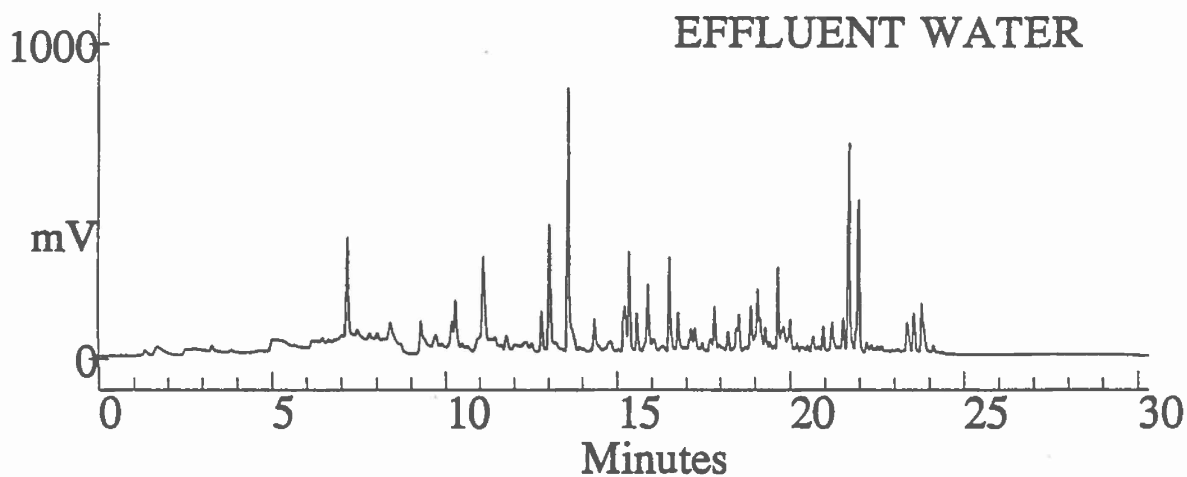
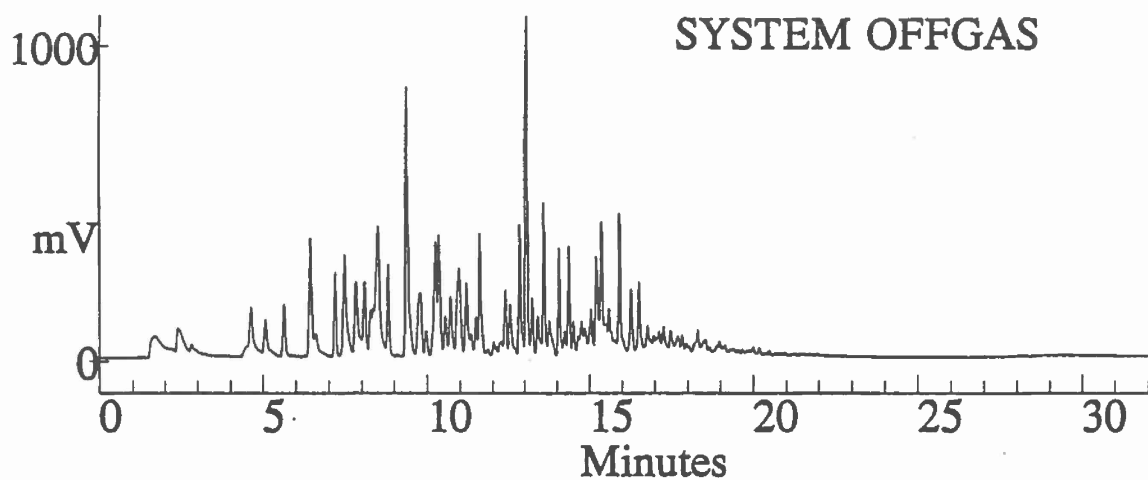
The water level measurements made across the well system indicated that a significant head developed from the air lift pumping. At an air flow rate of 1.0 cfm, the MBW system maintained between 2 and 3 feet of head, depending on ambient groundwater elevation, indicating groundwater was flowing through the well.

GC analyses of the influent, effluent, and off-gas from the MBW system showed that the system was efficient at stripping out the more volatile contaminants. The chromatograms in Figure 16 show the contaminant profile around the MBW system in September 1994. The lower chromatogram shows the hydrocarbon signature in the influent water. In general, the molecular weights of the hydrocarbon compounds increase, and the volatility of the hydrocarbon compounds decrease, as the time on the chromatograms increases (left to right). The middle chromatogram represents the water as it leaves the well system. Comparing the two chromatograms shows that the more volatile hydrocarbons (the left side of the chromatogram) have been effectively removed by the air stripping. The heavier, less volatile compounds remained in the water and were recirculated in the aquifer. The top chromatogram represents the hydrocarbon composition in the system off-gas. By comparing the chromatograms, it can be seen that the lighter compounds that were stripped were in fact in the vapor phase.

It was not possible to accurately calculate the water flow rate through the well using the head measurements because the piezometers were located just outside the well casing. To estimate the water flow rate, the analytical data from the chromatograms shown in Figure 16, and the known air flow rate, were used to construct a mass balance. Assuming conservation of mass of the water through the system, the only unknown was the water flow rate. The following equations were applied to the TPHs in the 11 molecular weight ranges to calculate a water flow rate based on their concentrations.

$$\text{TPH Flux}_{\text{infl}} = \text{TPH Flux}_{\text{effl}} + \text{TPH Flux}_{\text{off-gas}} \quad (1)$$

$$\text{TPH Flux}_{\text{infl}} = \text{Water Flow Rate} \times \text{Conc}_{\text{infl}} \quad (2)$$



**Figure 16. Chromatograms from GC Analyses of the Influent, Effluent, and Off-Gas Samples Collected in September 1994 from the MBW System.**

$$\text{TPH Flux}_{\text{effl}} = \text{Water Flow Rate} \times \text{Conc}_{\text{effl}} \quad (3)$$

$$\text{TPH Flux}_{\text{off-gas}} = \text{Air Flow Rate} \times (\text{Conc}_{\text{off-gas}} \times \text{CF}) \quad (4)$$

where:

TPH Flux<sub>infl</sub> = mass of TPH entering the well in the aqueous phase per unit time

TPH Flux<sub>effl</sub> = mass of TPH exiting the well in the aqueous phase per unit time

TPH Flux<sub>off-gas</sub> = mass of TPH exiting the well in the vapor phase per unit time

Water Flow Rate = volume of water entering or leaving the well per unit time

Air Flow Rate = volume of air injected into the well

Conc<sub>infl</sub> = mass of contaminant per unit volume of influent water

Conc<sub>effl</sub> = mass of contaminant per unit volume of effluent water

Conc<sub>off-gas</sub> = concentration of contaminant in air on a ppmv basis

CF = conversion factor from ppmv to mass per unit volume.

The results from these calculations are presented in Table 46. The average flow rate was calculated to be 4.53 L/min, and the median value was 3.26 L/min. Although there was a significant scatter in the calculated values (the CV was 69 percent), there was no apparent trend within the molecular weight ranges. Therefore, the flow rate was assumed to be approximately 4 L/min. Assuming this flow rate for the water, and using the air flow rate of 1.0 cfm, the air:water ratio was approximately 7. This ratio would be considered very low for air stripping and relatively high for air lift pumping (Powers, 1992) and suggests that neither the air lift pumping efficiency nor the air stripping efficiency was near maximum in the MBW system during this study.

The NaBr tracer study was conducted to determine travel times throughout the treatment volume in the aquifer. Although the test failed in this regard, the conductivity data (Table 19) did show that the MBW system moved water throughout the 25-foot radius of influence as assumed in the design. The data indicated that the water within the sphere of influence passed through the well system at least once within the 3 months between sampling for conductivity.

The groundwater TPH profiles in Figures 17, 18, 19, and 20 illustrate the changes in TPH distribution at 6, 9, 12, and 15 feet bgs, respectively, over the 12 months of operation. The profiles show that TPH concentrations in the groundwater changed significantly over the 3 months that the MBW system was operated. The well system was operated in an upflow mode, so the direction of water flow was away from the well at the shallower depths and toward the well at the deeper depths.

The TPH profiles show that, initially, there was heavily contaminated groundwater with TPH concentrations above 16,000 µg/L to the west of the well at the 6-foot depth and that the concentrations on the west side of the plot were generally higher. After 3 months, the hot spot had disappeared and the concentrations had decreased to below 9,000 µg/L. The TPH at the 9-foot depth did not show that much change with some shift and a slight increase

**TABLE 46. FLOW RATES CALCULATED USING INFLUENT, EFFLUENT, AND SYSTEM OFF-GAS TPH DATA**

<b>Molecular Weight Range</b>	<b>Flow Rate (cfm)</b>	<b>Flow Rate (liters/min)</b>
C5	0.083	2.35
C6	0.056	1.60
C7	0.036	10.3
C8	0.085	2.40
C9	0.289	2.22
C10	0.289	8.18
C11	0.146	4.70
C12	0.146	4.13
C13	0.272	7.69
C14	0.058	1.65
C15	BDL	BDL
Average	0.160	4.53

BDL - Below detection limit.

around the well system. At 12 feet bgs, the TPH concentration decreased slightly at the well. Initially, the groundwater on the northern end of the system was more heavily contaminated and the southern end was the cleaner. After 3 months of operation, this trend reversed. Groundwater at 15 feet bgs should be moving directly toward the well. The initial data indicated that the groundwater immediately adjacent to the MBW system was heavily contaminated, with TPH concentrations in excess of 16,000  $\mu\text{g/L}$ . After 3 months, the TPH concentrations in this area were significantly lower.

The mKGB system was started in October 1994, after the initial 3 months of operating the MBW system. The mKGB system maintained an approximately 0.9-foot head differential between the upper and lower screen, indicating that water was being pumped. Although this head differential was lower than the head differential observed at the same air flow rate on the MBW system, the flow rate was not necessarily lower. The MBW well was 4 inches in diameter, whereas the mKGB well was 8 inches in diameter. This meant that the mKGB system had approximately twice the amount of screen surface area and four times the cross-sectional area of the MBW system. Although the relationship between head in the



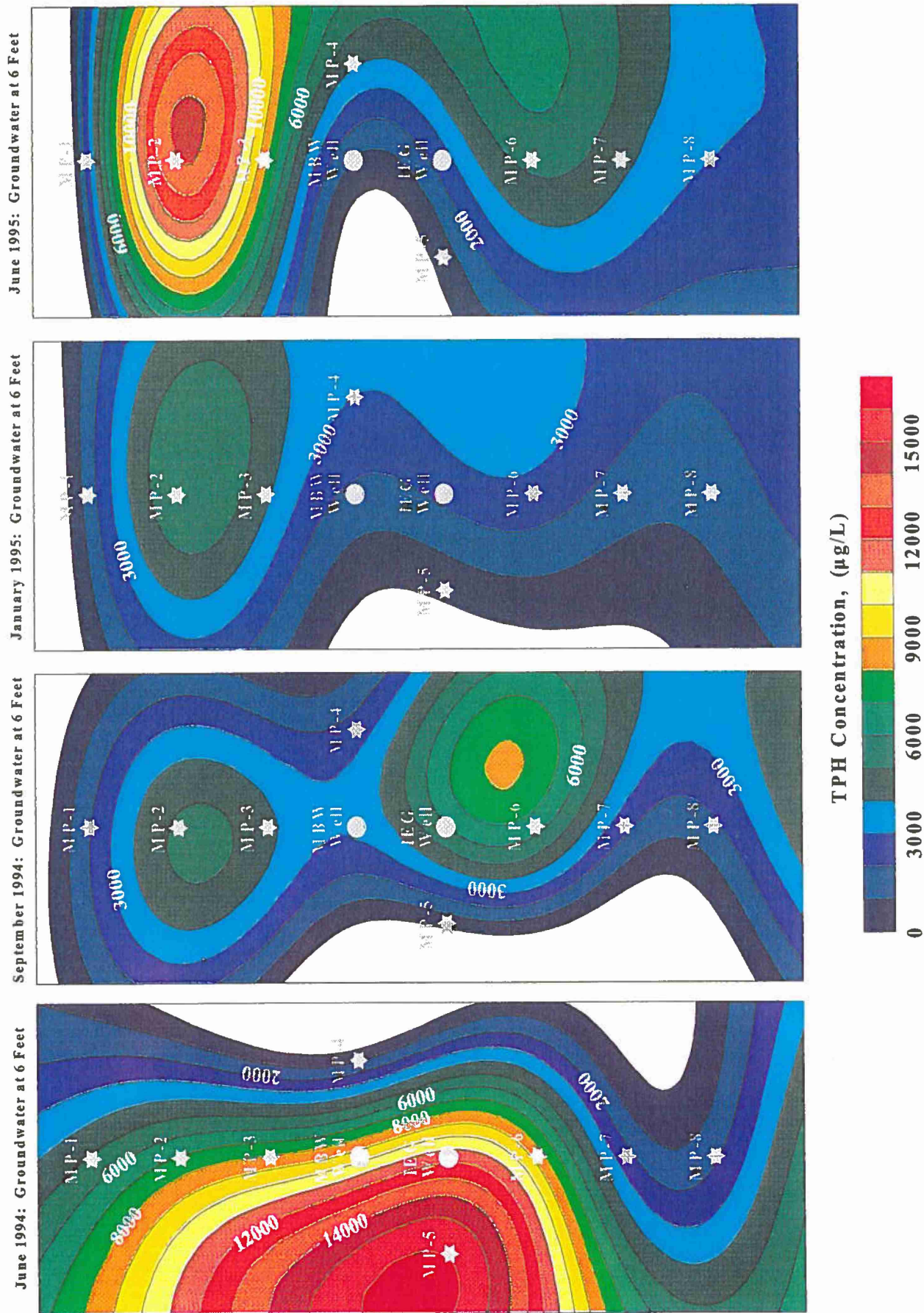


Figure 17. TPH Distribution in Groundwater at 6 Feet bgs During the In-Well Air Stripping Study at Tyndall AFB, Florida.



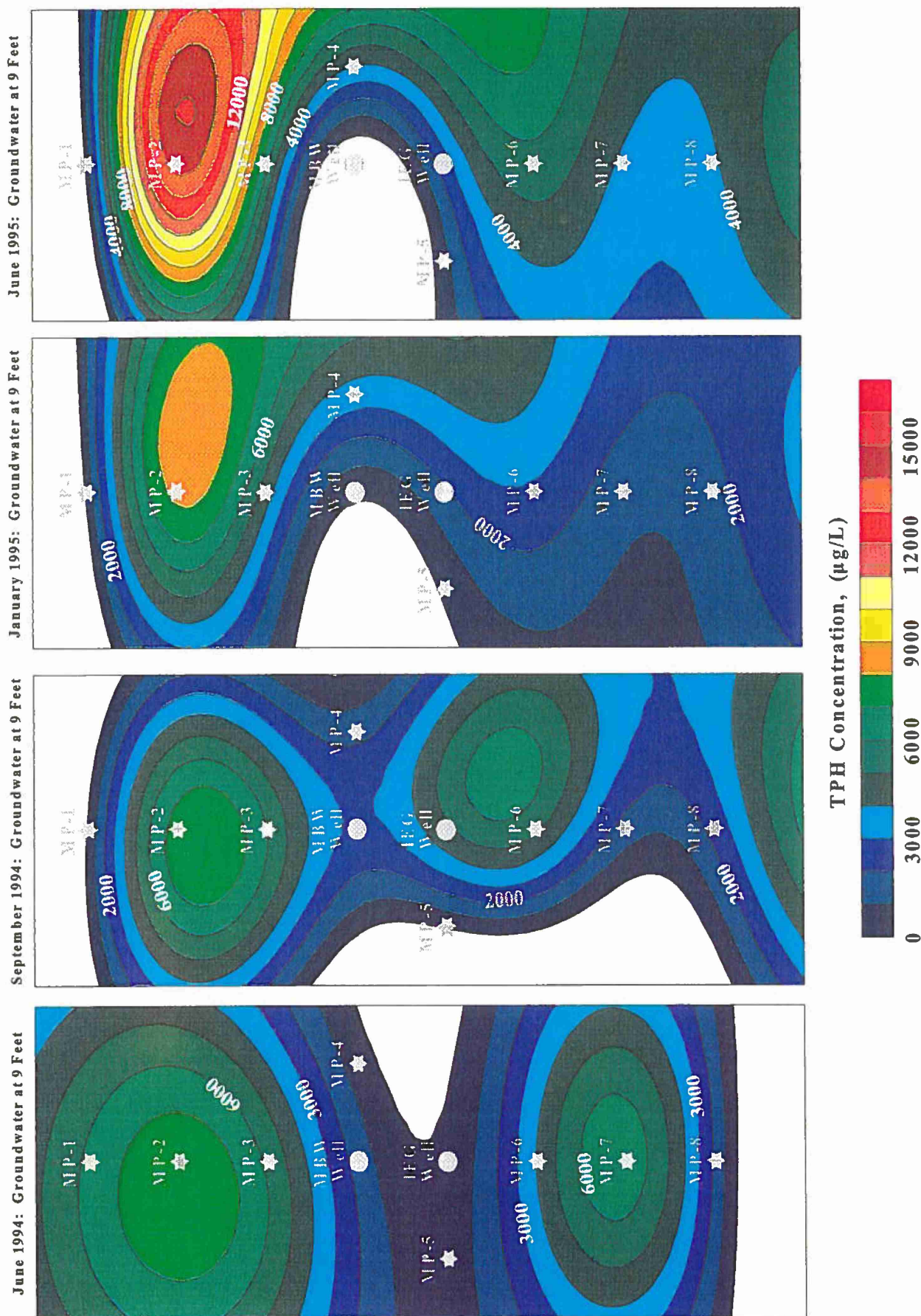


Figure 18. TPH Distribution in Groundwater at 9 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.



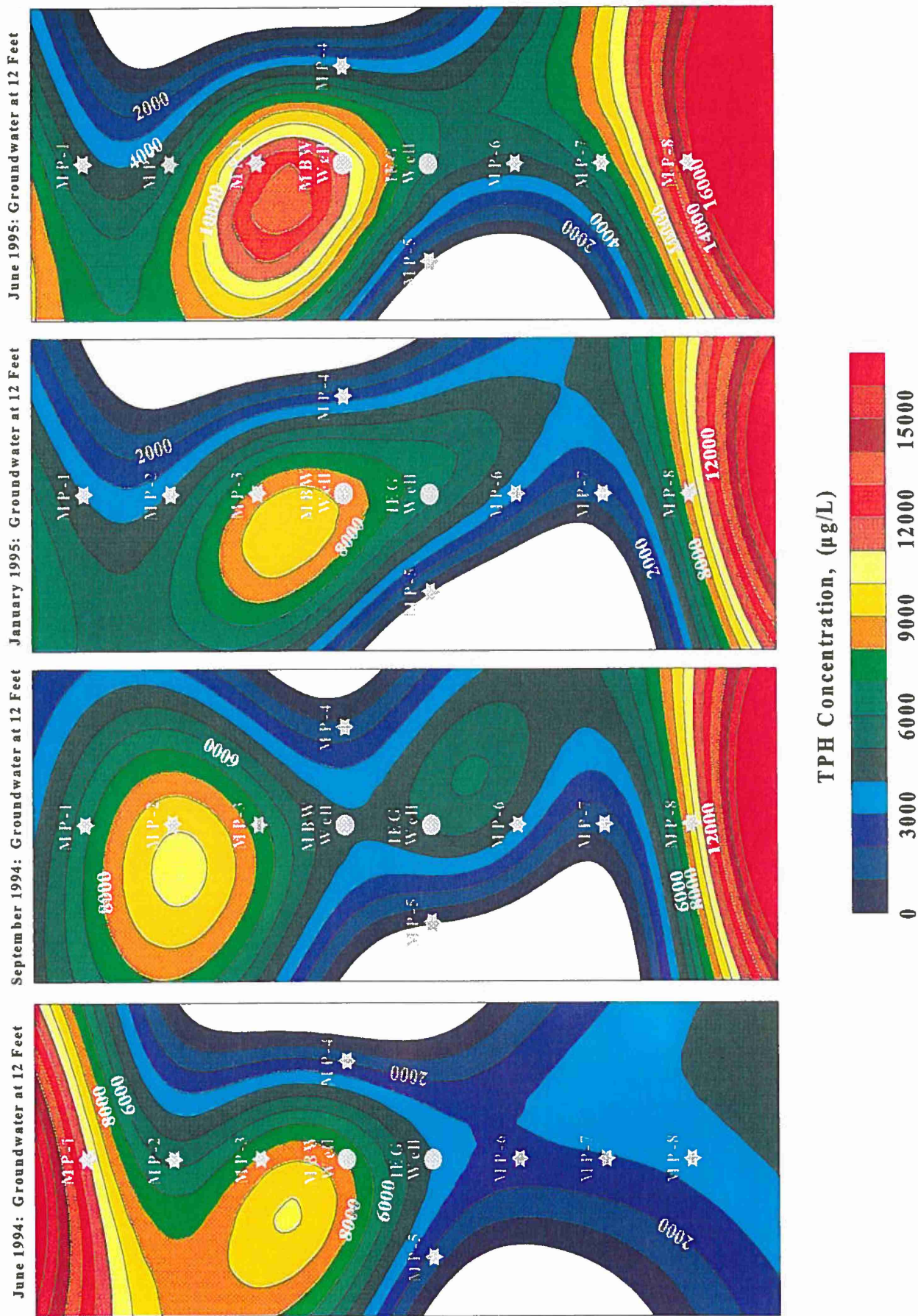


Figure 19. TPH Distribution in Groundwater at 12 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.



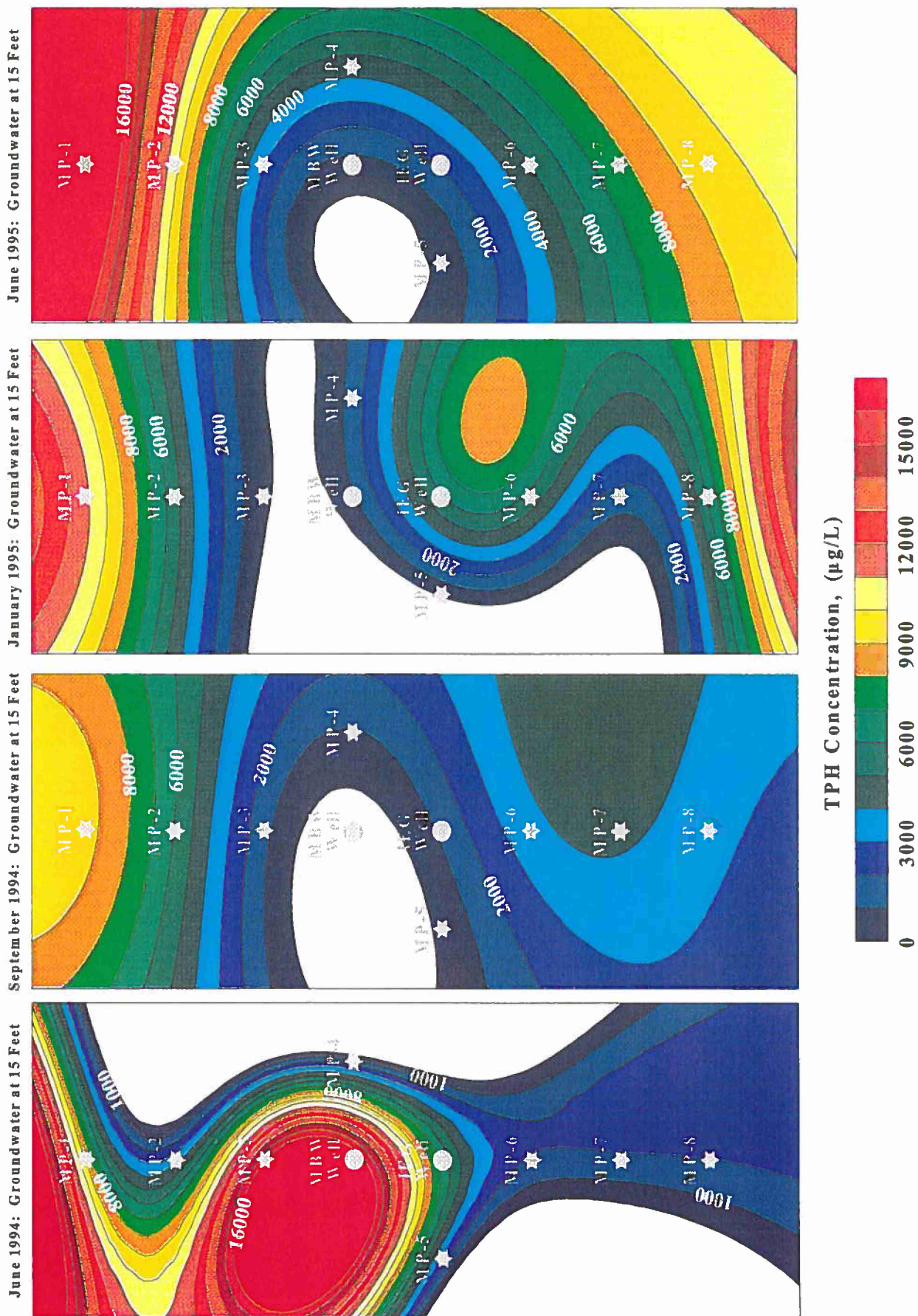


Figure 20. TPH Distribution in Groundwater at 15 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.

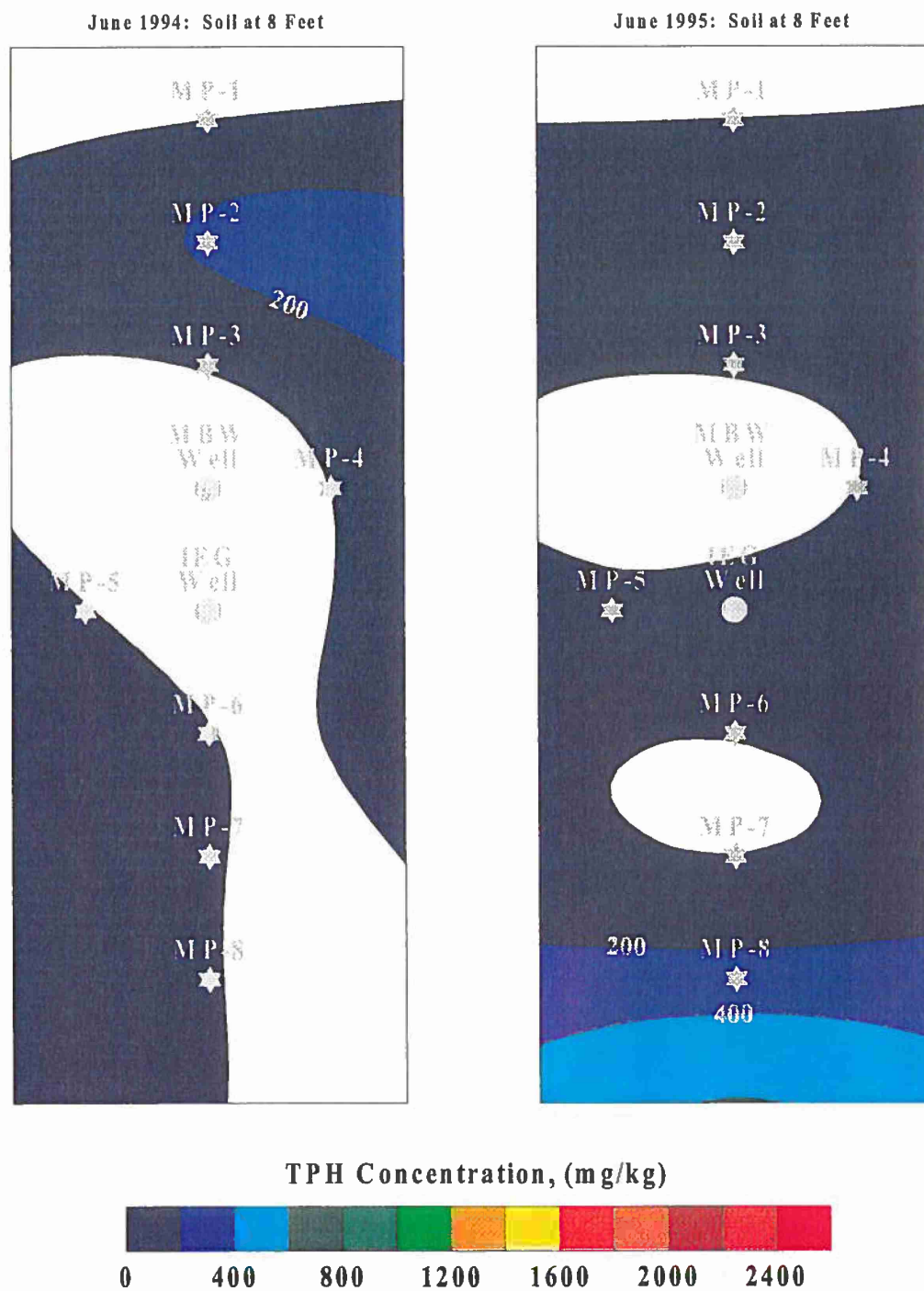
piezometers and flow was not apparent, it is conceivable that the mKGB well system was moving at least as much water as the MBW system.

Unfortunately, the data from the mKGB well were not useful for calculating a flow rate because of the low concentration of TPH and because there appeared to be a significant amount of mixing within the well casing. TPH concentrations in water samples collected from the upper and lower sections of the well, and in the sample of the system off-gas in January and June 1995, were very low. In each case, the concentrations in water from the lower section of the well were lower than the concentrations in samples from the upper screen.

The fact that the TPH concentrations within the well and in the system off-gas were so low, and the TPH concentrations in the groundwater outside the well were significantly higher, suggests that the well was short-circuiting around itself. The problem may have arisen when the well casing was installed. There was a significant problem with heaving sand during installation, and the casing may have shifted during completion. Improper placement of the bentonite seal and sand pack could have resulted in creation of preferential flow paths for water within the annulus of the borehole.

Although it was not possible to evaluate the pumping rate of the mKGB system using the contaminant data, the groundwater TPH profiles shown in Figures 17, 18, 19, and 20 show changing TPH distributions that indicate the system was moving water. At 6 feet bgs, the TPH concentrations adjacent to the well and to the south decreased significantly between September 1994 and January 1995. A similar trend was observed at 9 feet bgs. The profiles at the 12- and 15-foot depths show more heavily contaminated groundwater moving towards the well from both north and south of the well. This is consistent with the groundwater movement established by the air lift pumping and groundwater circulation.

The in-well air stripping system needed to provide remediation of the aquifer soils, in addition to remediation of the groundwater, in order for the technology to be effective. The TPH profiles shown in Figure 21 and 22 were developed using the data from the initial and final soil samples collected from 8 and 12 feet bgs. The profiles show how the TPH concentrations were impacted by the combined operation of the MBW and mKGB systems. As is expected with JP-4 contamination, the TPH concentrations at these depths were significantly lower than in the smear zone at 4 feet bgs. In general, the initial concentrations were below 600 mg/kg. The profile from 12 feet bgs shows that the soil TPH concentrations decreased to the west and increased to the east of the well systems. The water moves toward the well at this depth, which means that the water circulation may have pulled contaminant from a more heavily contaminated area on the east toward the well and the area on the west is not as heavily contaminated. The profile for the 8-foot depth shows the impact from water moving out from the well systems. The profiles show a slight decrease towards the north and an increase in the TPH concentration adjacent to the wells and to the south. The increase shown to the south may not be real, as the concentrations in this area of the profile are extrapolated by the computer program.



**Figure 21. Initial and Final TPH Distributions in Soil at 8 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.**



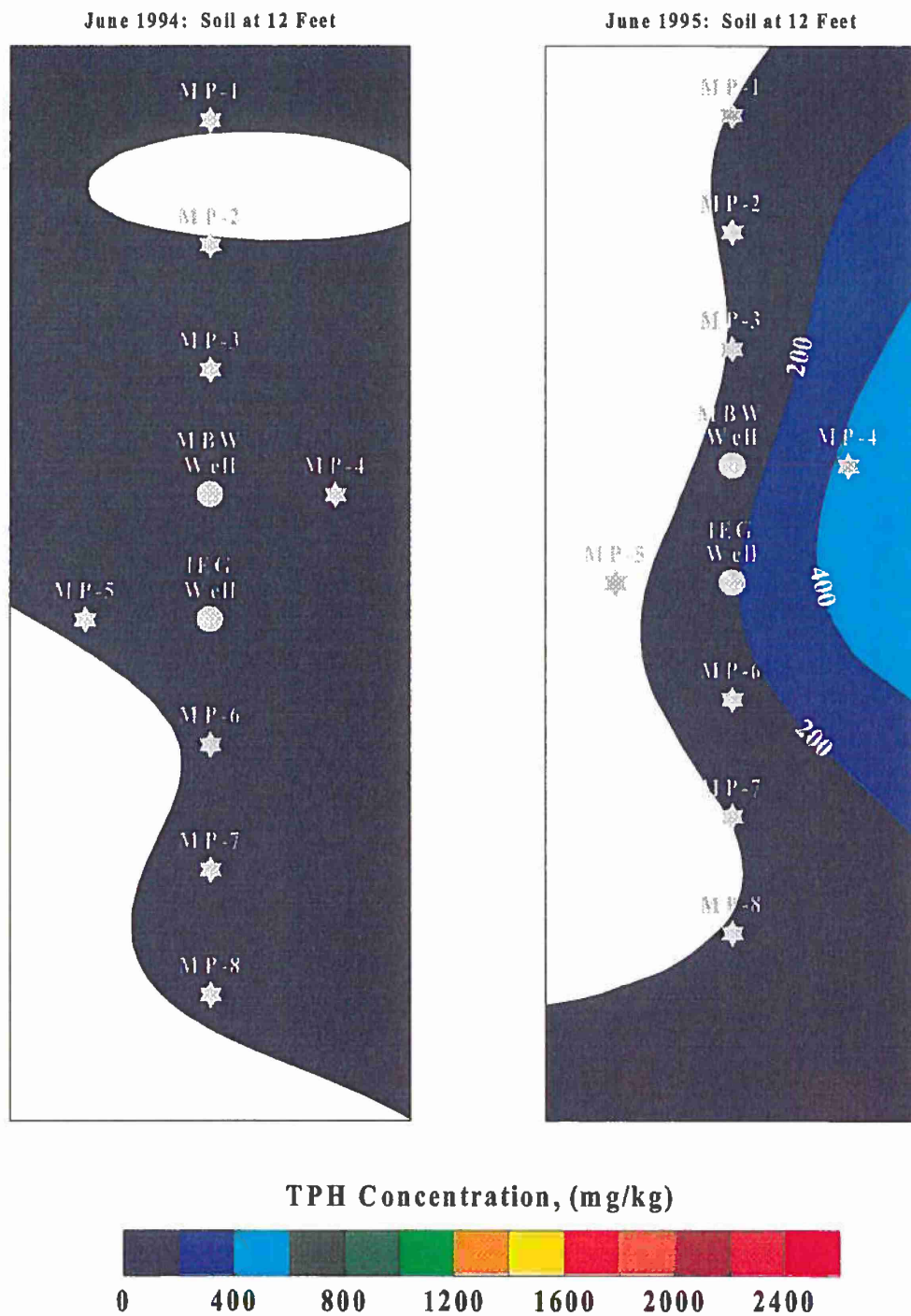


Figure 22. Initial and Final TPH Distributions in Soil at 12 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.

Overall, it is difficult to determine any significant degree of remediation of the TPH in the soils below the water table. The TPH concentrations were low to begin with and, although the profiles changed, there was no net reduction in TPH concentrations. It was observed that there was no increase in DO at any of the points at any depth. Reductions in TPH levels would rely on mass transfer to the well system. If O<sub>2</sub> were more effectively delivered, it is conceivable that the reduction in TPH in the aquifer would have been more significant.

## **B. BIOVENTING COMPONENT**

Bioventing was the contaminant destruction component of the coupled technology. The process exploits the degradative activity of indigenous microorganisms to provide this destruction through aerobic metabolism. Typically, bioventing systems include forced air movement through either air injection or withdrawal using a system of blowers, air distribution manifolds, and vent wells. The system studied at Tyndall AFB utilized the off-gas from the in-well air stripping systems to provide the necessary air movement and oxygen delivery in the vadose zone to support the bioventing component.

Although bioventing is a proven technology for treating petroleum hydrocarbon contamination in the vadose zone, the objective of this study was to determine if the well systems could support bioventing and if the indigenous microorganisms could biodegrade both the residual contamination in the vadose zone soils and the contaminants introduced in the off-gas from the well systems. The oxygen remaining in the air after stripping and oxygenation of the groundwater would need to satisfy the requirement for aerobic degradation of the hydrocarbon. If the well system could not support bioventing and/or bioventing could not keep up with the in-well air stripping system, degradation of the hydrocarbon in the vadose zone would be slow, and hydrocarbon vapors from soil pore spaces and the well system off-gas would be emitted from the ground surface.

Two surface emission tests were conducted to determine if the bioventing component would be able to handle the volatile hydrocarbons in the system. The first test was conducted in September 1994, during operation of the MBW system. The data showed that fewer hydrocarbon vapors were emitted when the system was operating than when it was turned off. This observation was not attributed to dilution of the hydrocarbon due to the system airflow because the mass loading of hydrocarbon from the well component into the vadose zone was more than 16 times greater than the flux from the system. The lower flux rate during operation was attributed to increased microbial degradation capacity during operation, when the soils were aerobic and the microorganisms were supplied with sufficient oxygen to support aerobic biodegradation. After the system was shut off, the oxygen levels in the soil decreased. When they fell below 5 to 8 percent, degradation became oxygen-limited and hydrocarbons that were not being degraded began to diffuse from the ground surface.

The second surface emission test was conducted in January 1995, when the mKGB system was operating. During this test, the hydrocarbon emissions were significantly higher

when the system was running, indicating that the bioventing component was not keeping up with the well system. The primary reason for this observation is that the microbial activity in January is lower than during the warmer months. As the temperature drops, so do the degradation rates, and the transport of hydrocarbon vapors through the system can exceed the degradative capacity (Miller et al, 1991).

Even though the emission of hydrocarbon was higher during operation of the mKGB system in January, the total flux rate attributed to operation of the system was very low. Typically, off-gas treatment is required when benzene emissions exceed 1 lb/day. Because the total TPH emission rate attributed to operation of the system at Tyndall in January was  $5.1 \times 10^{-4}$  lb/day, well below the regulatory level, off-gas treatment was not required. Although it would be possible to lower the air flow rate of the well system to reduce surface emissions, it would not be desirable because of the impact on the air lift pumping efficiency and the delivery of oxygenated water.

In addition to the surface emission tests, three in situ respiration tests were conducted to directly monitor the microbial activity in the vadose zone. The tests were conducted in September, January, and June so that the effect of temperature could be examined. The oxygen utilization rates measured in the field were converted into biodegradation rates (Hinchee et al., 1992). The average biodegradation rates ranged from just below 1.0 mg-TPH/kg-soil-day in January to more than 7.0 mg-TPH/kg-soil-day in June. Unfortunately, the soil gas sampling pump developed a leak during the September test and the validity of the data from that test are in question. The soil temperatures in January and June were approximately 17°C and 27°C, respectively, whereas in September the average temperature was approximately 26°C. These temperatures indicate that the rates observed in September should have been in between the rates observed in January and June, closer to the June rates. The temperature data indicated that the biodegradation rates at the Tyndall site were strongly influenced by temperature, with over a sevenfold decrease in the rate with a 10°C temperature change.

Another parameter against which to evaluate the effectiveness of the bioventing component is the decrease in TPH concentrations in the soil gas over time. When soils are anoxic and aerobic biodegradation is limited, TPH concentrations increase in the soil gas. When the soils are sufficiently aerated, biodegradation rates increase and the vapor concentrations are reduced. Figures 23 and 24 illustrate how the TPH concentrations in the soil gas changed at the 2- and 4-foot depths, respectively, over the duration of the test. Initially, a TPH "hot spot" characterized by TPH concentrations as high as 6,000 ppmv was apparent in the center of the treatment area at 2 feet bgs. By September, this hot spot was no longer apparent and the concentrations had dropped to below 1,000 ppm at all locations. By the end of the study, the TPH profile showed that an area in the center of the system had significantly reduced levels of TPH. The soil gas profiles for the 4-foot depth show the same trend. The north end of the system around MP-1 was extremely hot with TPH concentrations in excess of 12,000 ppmv. By September, the hot spot was no longer evident and the TPH concentrations in the soil gas from all locations were below 2,000 ppm. By January, the TPH level had decreased to below 1,000 ppm at all points, and the profile



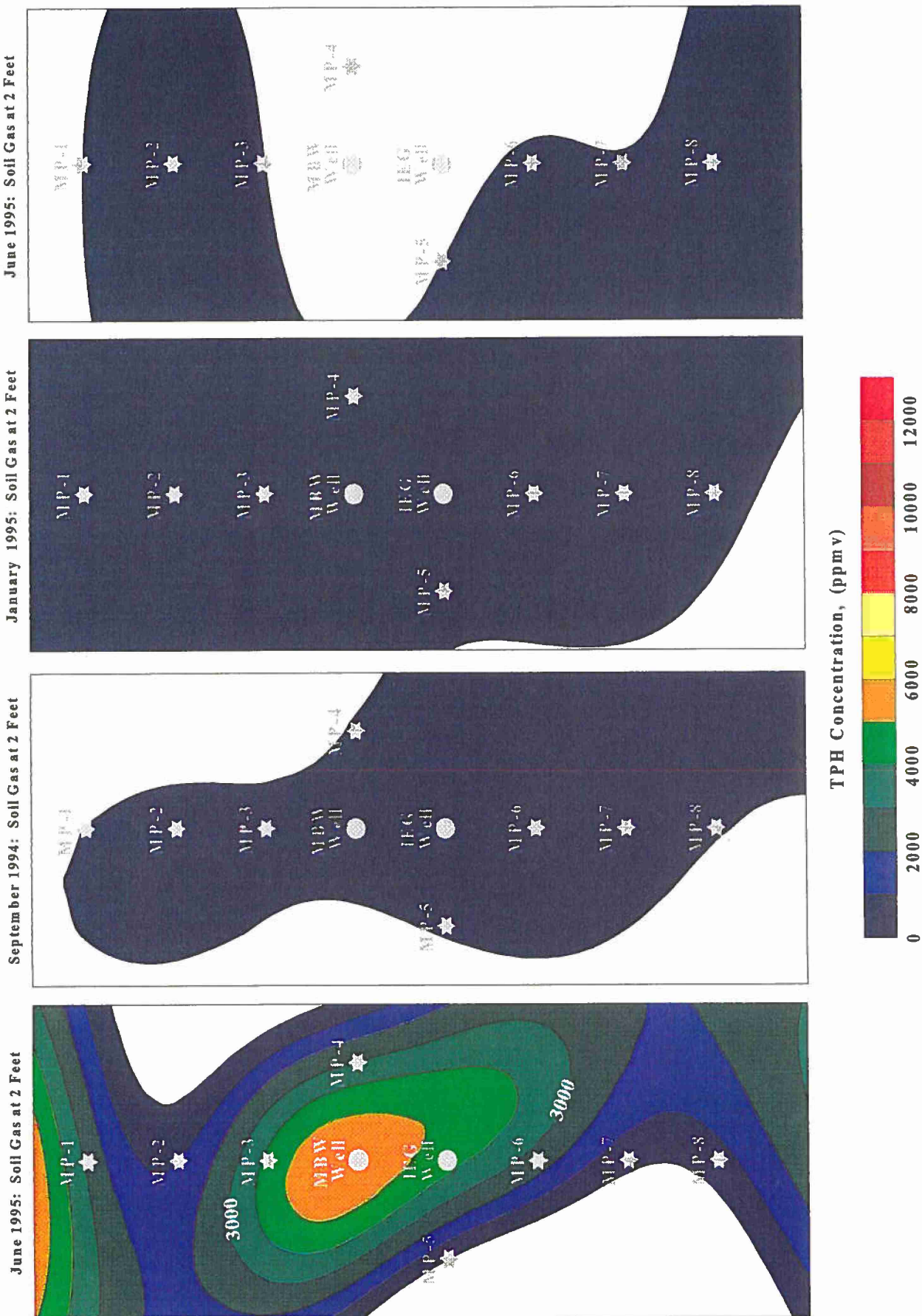


Figure 23. Soil Gas TPH Profiles 2 Feet Bgs During the In-Well Air Stripping/Bioventing Demonstration Study at Tyndall AFB, Florida.

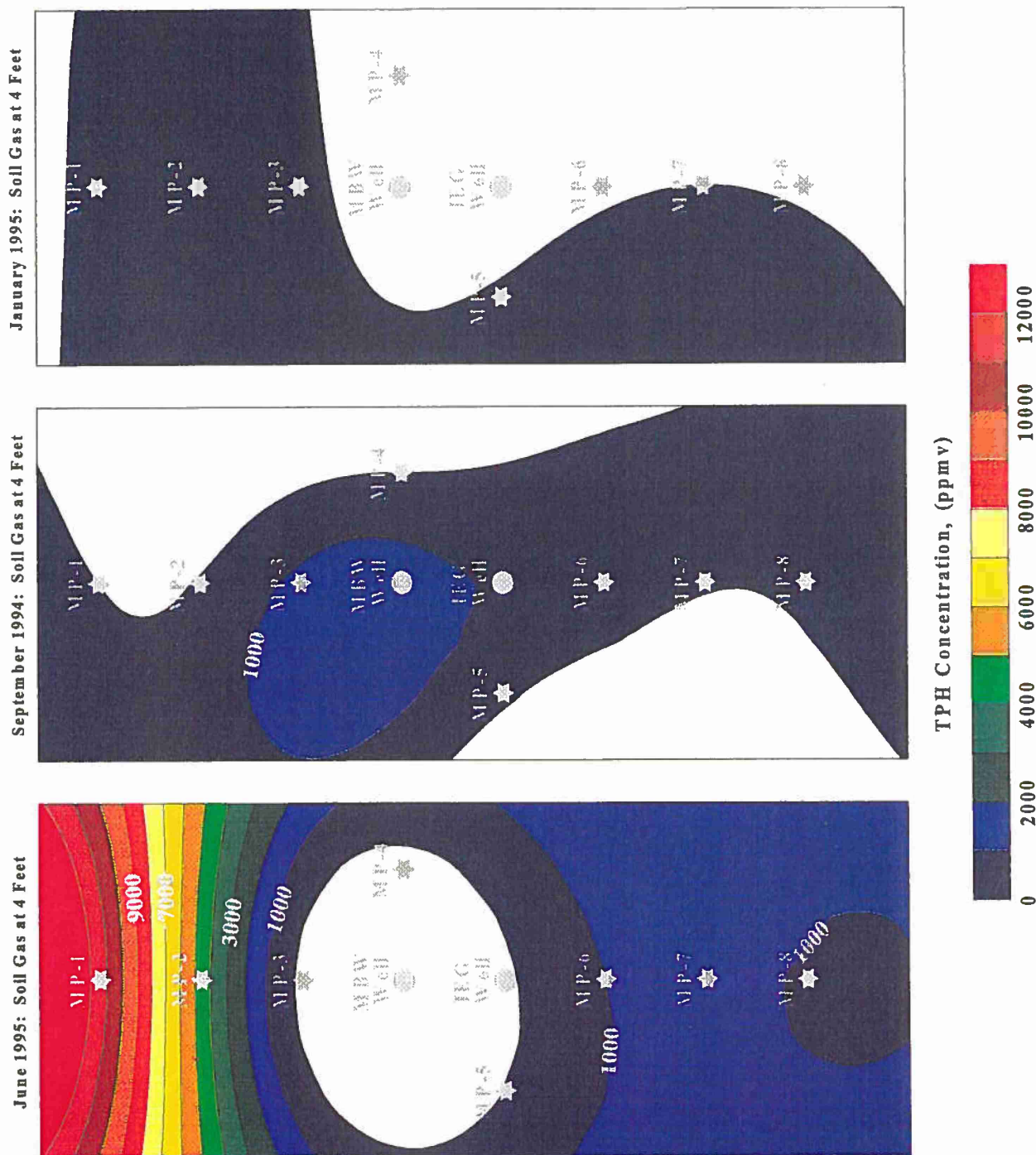


Figure 24. Soil Gas TPH Profiles 4 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.

indicated very low levels in the southeast section of the treatment area. The bioventing component was very effective at reducing the soil gas TPH concentrations.

The final and perhaps the most important criterion for evaluating the effectiveness of bioventing is the reduction of TPH in the soil. Figure 25 shows the TPH profiles from soil samples collected from 4 feet bgs before and after system operation. The profiles show how effective bioventing was at achieving this reduction at the Tyndall AFB site. Initially, the soil contained TPH at concentrations ranging from less than 200 mg/kg to more than 2,400 mg/kg. The north end of the treatment area was the most contaminated, and the central and southern sections were the least contaminated. After 1 year of operation, the TPH in the soil was reduced significantly. The hot spot in the northern end was no longer apparent, and the concentrations in the treatment area had been reduced to between less than 200 mg/kg to 600 mg/kg.

Based on the change in the TPH profile shown in Figure 25, it appears that the microbial activity on the north side of the treatment area was higher than on the southern side. However, this may not be the case. The groundwater profiles indicate that highly contaminated groundwater was moving into the treatment area from the south. If there is free product on the surface of any groundwater entering the treatment area, fluctuations in the water table could cause a smearing of the hydrocarbon in the soils at 4 feet bgs.

Overall, the data indicate that the bioventing component of the system used in this study was very effective in both handling the TPH vapors in the off-gas from the well systems and reducing the TPH concentrations in the soil.

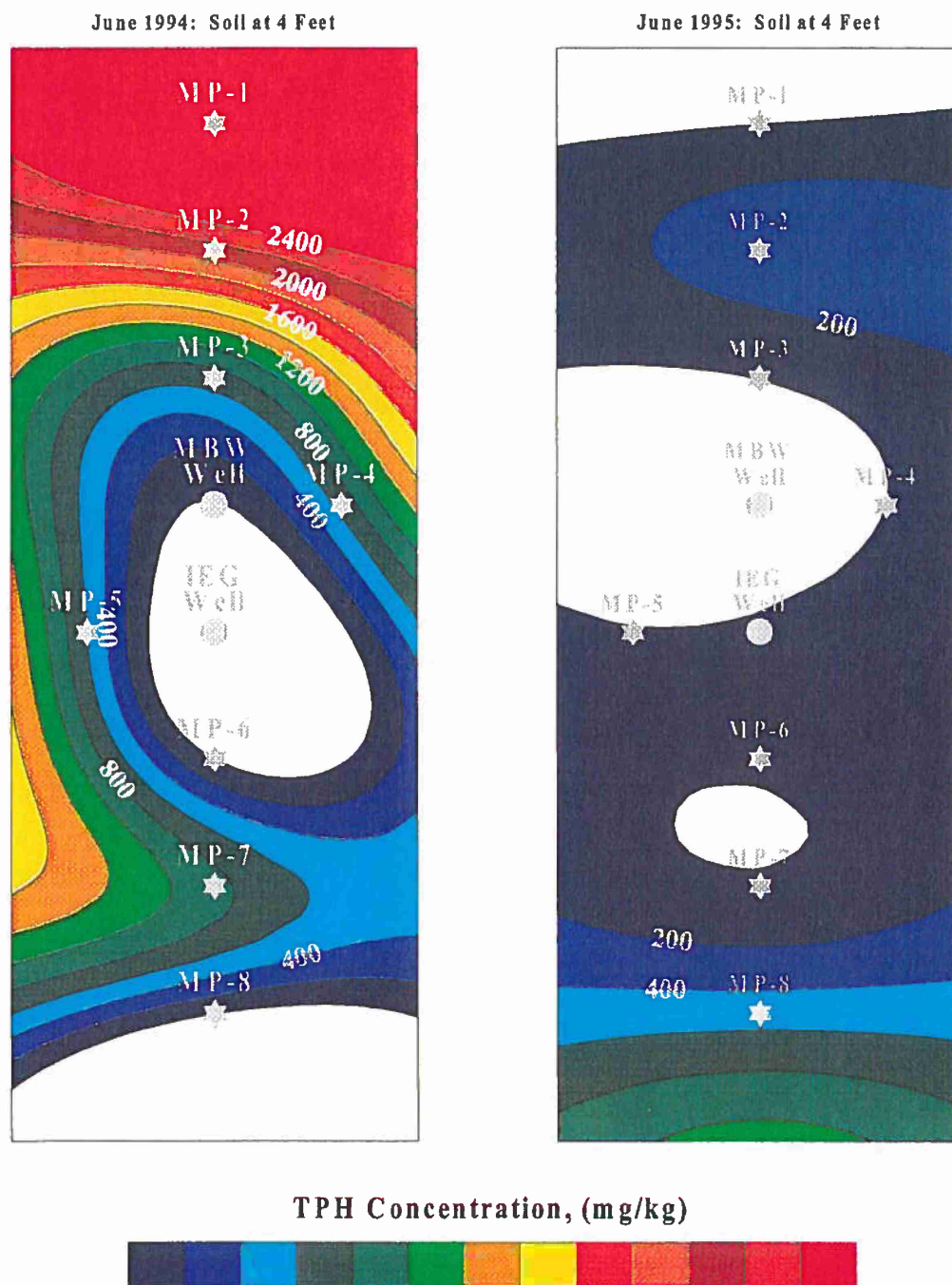


Figure 25. Initial and Final Soil TPH Profile 4 Feet bgs During the In-Well Air Stripping/Bioventing Study at Tyndall AFB, Florida.



## SECTION V CONCLUSIONS

The data collected during this study proved useful for evaluating the potential for extending bioventing to simultaneously remediate petroleum hydrocarbon contamination both above and below the water table by incorporating in-well air stripping systems into the bioventing system design. Although there was no attempt to optimize the systems with regards to either pumping and/or air stripping efficiency, the following conclusions were made.

1. The air lift pumping mechanism was capable of circulating groundwater in the aquifer without the need of pumping water out of the aquifer and reinjecting it through a distribution system.
2. The volatile compounds were effectively stripped from the groundwater by the injected air during air lift and effectively transferred to the vadose zone.
3. Anoxic groundwater entering the well was sufficiently oxygenated during air lift; however, the amount of oxygen that was delivered through recirculated water could not meet the oxygen demand, such that aerobic biodegradation in the saturated zone at points distant from the well was limited.
4. The residual oxygen in the off-gas from the in-well air stripping system was sufficient for supporting bioventing in the vadose zone.
5. Volatile compounds in the off-gas from the well system were degraded in the vadose zone through bioventing when the mass loading did not exceed the degradative capacity of the microorganisms.
6. Bioventing was very effective for remediating residual hydrocarbon contamination in the vadose zone.

Overall, the study proved that extending bioventing through incorporation of in-well air stripping was feasible and that development of the technology should be pursued.

## SECTION VI RECOMMENDATIONS

The coupling of the in-well air stripping and bioventing technologies proved successful in this study. However, this was conducted as a feasibility study to test the coupling of two proven technologies and was not meant to provide design, operating, and/or cost information for the implementation of the coupled technology. This study was to serve as the first step in the development of a technology that would extend the application of bioventing to simultaneously remediate contamination above and below the water table. Because the coupling was successful, the following recommendations are made as next steps in the development of a viable technology:

1. An investigation into ways to increase the efficiency of oxygen delivery in the saturated zone should be conducted. The existing system at Tyndall AFB would be well suited for such a study. Two potential ways of accomplishing this are to increase the oxygen partial pressure in the injected air through the use of a pressure swing oxygen generator in between the compressor and the well system. The other method would be to combine air sparging with the use of the in-well air stripping system. The wells facilitate circulatory movement of the groundwater in the aquifer, and the air sparging system would serve to both strip volatiles at points distant from the well and oxygenate the groundwater to support biodegradation below the water table. The data from this study indicated that the contamination in the vadose zone, and possibly the volatile fraction of the contamination in the saturated zone, would be remediated significantly faster than the residual hydrocarbon in the aquifer matrix. Accomplishing enhanced oxygen delivery into the saturated zone could decrease the time required for remediation by supporting aerobic biodegradation in a larger portion of the treatment cell.
2. Although the sorbent tubes were effective for collecting the 19 compounds that comprised the JP-4 fingerprint, it is recommended that whole air samples be collected when monitoring TPH concentrations in the soil gas. The sorbent tube data did not always agree with the TPH data generated by the field instruments. In all cases where there was disagreement between methods, the tube concentrations were significantly lower than the field readings. This could be due to lighter hydrocarbons not being effectively retained by the sorbent materials in the tubes and hence not being accounted for during GC analyses. Whole air samples collected in Summa polished canisters would provide a more accurate measurement of TPH levels in the gas, and should help reduce the discrepancies between field and laboratory analyses.
3. An in-well air stripping/bioventing demonstration should be conducted at a site where the process can be experimented with so that operational data can be collected. A site would need to be selected that is contaminated with sufficient levels of hydrocarbon in both the vadose and saturated zones. The experiments

should be conducted so that the process variables are changed over time to determine the cause-and-effect relationships. The site should be characterized with a deep vadose zone having characteristics amenable to bioventing and a thick aquifer characterized with a hydraulic conductivity conducive to groundwater circulation. The water table should be deep enough so that the system air flow rate can be optimized without excessive surface emissions of TPH vapors. The study should be designed to provide both design and cost data for the implementation of the coupled technology.

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## **APPENDIX A**

### **OXYGEN AND CARBON DIOXIDE DATA AND REGRESSION ANALYSIS OUTPUT FOR RESPIRATION TEST 1**

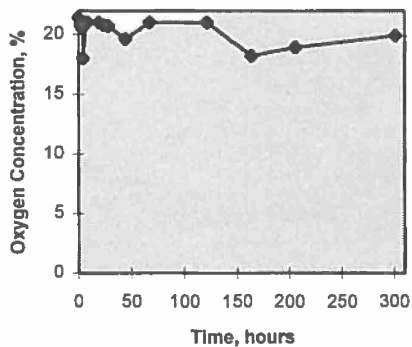
**In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994**

**Oxygen Data**

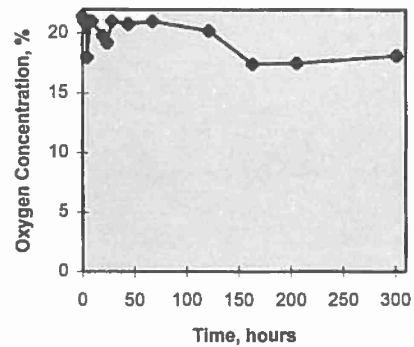
Date	MP -1			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	21.4	0	21
9/20/94	1.5	20.8	1.5	19.5
9/20/94	3.25	20.5	3.25	19.2
9/20/94	4.5	18	4.5	17
9/20/94	8	21	8	19.8
9/20/94	9.25	21	9.25	19.8
9/21/94	19.75	21	19.75	19.9
9/21/94	24	20.8	24	19.8
9/21/94	28.5	20.7	28.5	19.5
9/22/94	44.5	19.6	44.5	20.5
9/23/94	67.5	21	67.5	19.8
9/25/94	122	21	122	20.9
9/27/94	164	18.2	164	18.9
9/29/94	206	18.9	206	18.5
10/3/94	301.5	19.9	301.5	19.8

MP -2			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	21.4	0	21
1.5	21	1.5	19.5
3.25	20.8	3.25	19.7
4.5	18	4.5	17
8	21	8	19.7
9.25	21	9.25	20.5
19.75	19.8	19.75	21
24	19.2	24	21
28.5	21	28.5	19.1
44.5	20.8	44.5	18.4
67.5	21	67.5	21
122	20.2	122	20.5
164	17.4	164	19.9
206	17.5	206	18.5
301.5	18.1	301.5	19.8

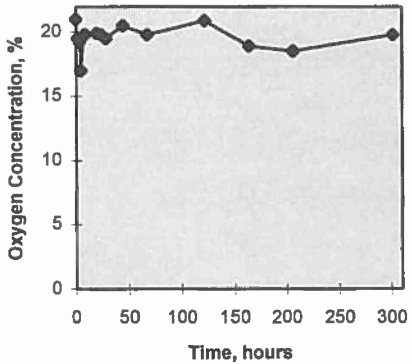
**Oxygen at MP-1 2 ft**



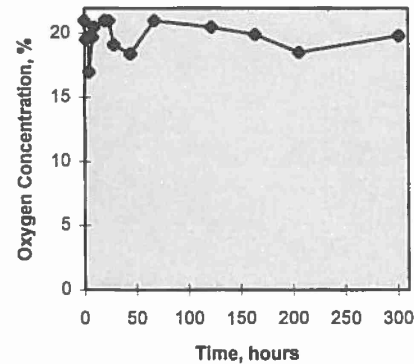
**Oxygen at MP-2 2 ft**



**Oxygen at MP-1 4 ft**



**Oxygen at MP-2 4 ft**

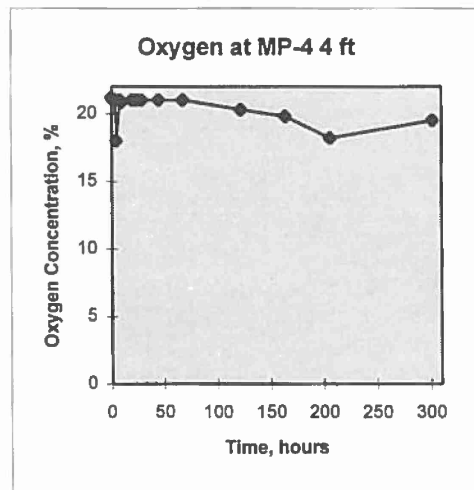
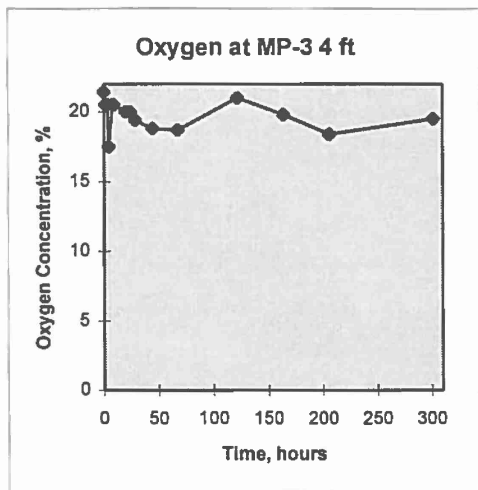
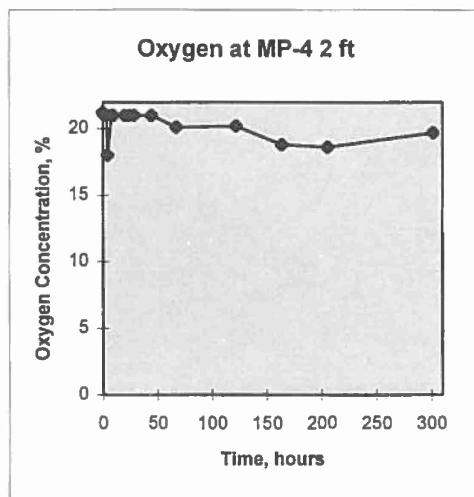
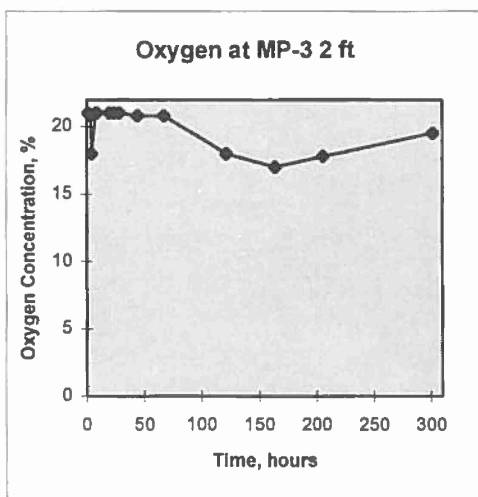


**In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994**

**Oxygen Data**

MP -3				
Date	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	21.3	0	21.4
9/20/94	1.5	21	1.5	20.5
9/20/94	3.25	20.8	3.25	20.5
9/20/94	4.5	18	4.5	17.5
9/20/94	8	21	8	20.5
9/20/94	9.25	21	9.25	20.5
9/21/94	19.75	21	19.75	20
9/21/94	24	21	24	20
9/21/94	28.5	21	28.5	19.4
9/22/94	44.5	20.8	44.5	18.8
9/23/94	67.5	20.8	67.5	18.7
9/25/94	122	18	122	21
9/27/94	164	17	164	19.8
9/29/94	206	17.8	206	18.4
10/3/94	301.5	19.5	301.5	19.5

MP -4			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	21.2	0	21.2
1.5	21	1.5	21
3.25	21	3.25	21
4.5	18	4.5	18
8	21	8	21
9.25	21	9.25	20.8
19.75	21	19.75	21
24	21	24	21
28.5	21	28.5	21
44.5	21	44.5	21
67.5	20.1	67.5	21
122	20.2	122	20.3
164	18.8	164	19.8
206	18.6	206	18.2
301.5	19.7	301.5	19.5



**In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994**

**Oxygen Data**

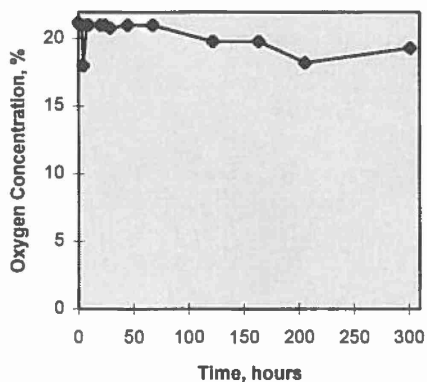
**MP -5**

Date	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	21.2	0	21.2
9/20/94	1.5	21	1.5	20.5
9/20/94	3.25	21	3.25	20.5
9/20/94	4.5	18	4.5	17.7
9/20/94	8	21	8	20.5
9/20/94	9.25	21	9.25	20.5
9/21/94	19.75	21	19.75	20.5
9/21/94	24	21	24	20.7
9/21/94	28.5	20.8	28.5	20.5
9/22/94	44.5	21	44.5	20.4
9/23/94	67.5	21	67.5	20.5
9/25/94	122	19.8	122	20.1
9/27/94	164	19.8	164	19.5
9/29/94	206	18.2	206	18.2
10/3/94	301.5	19.3	301.5	19.2

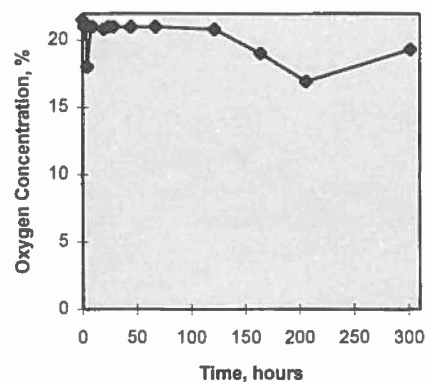
**MP -6**

Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	21.5	0	21.5
1.5	21	1.5	21
3.25	21	3.25	19.5
4.5	18	4.5	16.5
8	21	8	19.5
9.25	21	9.25	19.5
19.75	20.8	19.75	19.3
24	21	24	19
28.5	21	28.5	18.8
44.5	21	44.5	18.8
67.5	21	67.5	19.3
122	20.8	122	20.1
164	19	164	19.6
206	16.9	206	18.7
301.5	19.3	301.5	19.2

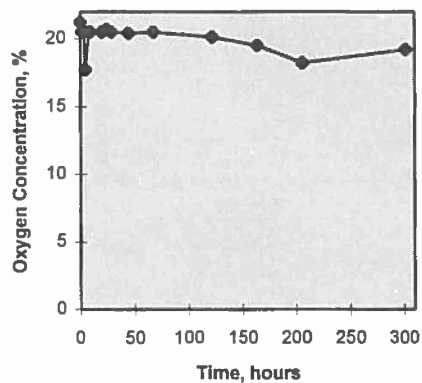
**Oxygen at MP-5 2 ft**



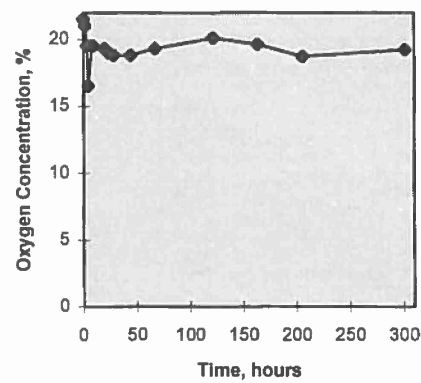
**Oxygen at MP-6 2 ft**



**Oxygen at MP-5 4 ft**



**Oxygen at MP-6 4 ft**



In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994

Oxygen Data

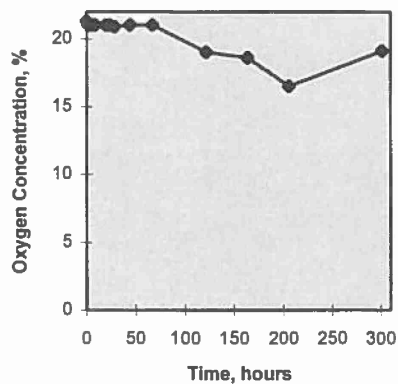
MP -7

Date	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	21.3	0	21.4
9/20/94	1.5	21	1.5	20.5
9/20/94	3.25	21	3.25	20
9/20/94	4.5	21	4.5	20
9/20/94	8	21	8	20
9/20/94	9.25	21	9.25	20
9/21/94	19.75	21	19.75	19.6
9/21/94	24	21	24	19.5
9/21/94	28.5	20.9	28.5	19.1
9/22/94	44.5	21	44.5	18.9
9/23/94	67.5	21	67.5	19.2
9/25/94	122	19	122	20.6
9/27/94	164	18.6	164	19.1
9/29/94	206	16.5	206	18.6
10/3/94	301.5	19.1	301.5	19

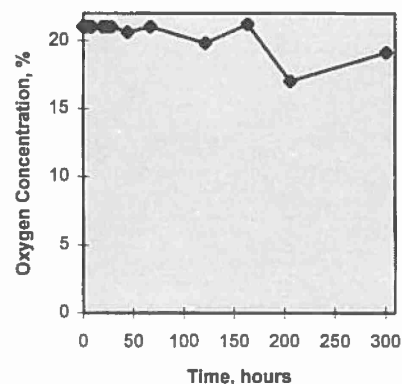
MP -8

Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	21	0	21.2
1.5	21	1.5	20.5
3.25	21	3.25	20.5
4.5	21	4.5	20.5
8	21	8	20.5
9.25	21	9.25	20.5
19.75	21	19.75	20
24	21	24	19.9
28.5	21	28.5	19.5
44.5	20.6	44.5	19.3
67.5	21	67.5	19.5
122	19.8	122	20
164	21.2	164	19.2
206	17	206	18.4
301.5	19.1	301.5	19

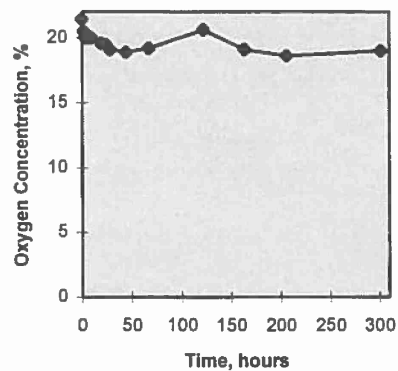
Oxygen at MP-7 2 ft



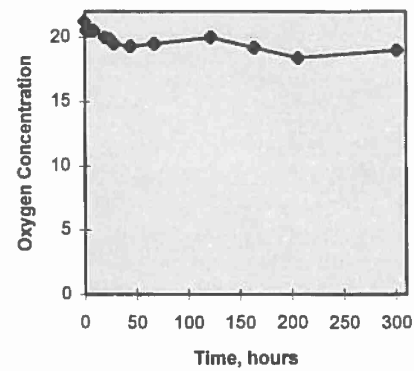
Oxygen at MP-8 2 ft



Oxygen at MP-7 4 ft



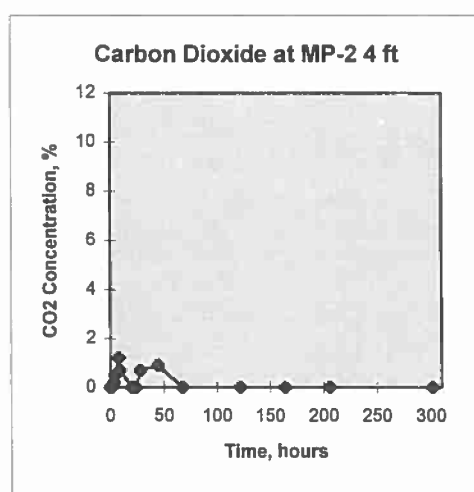
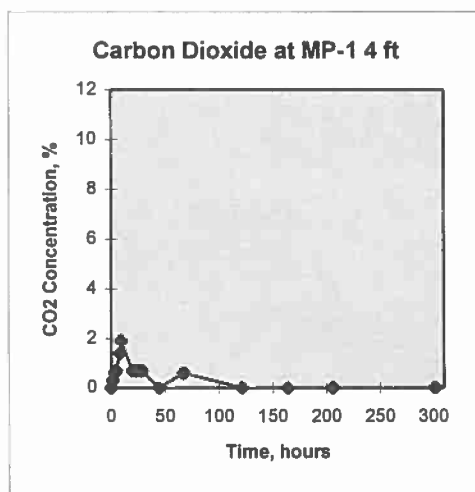
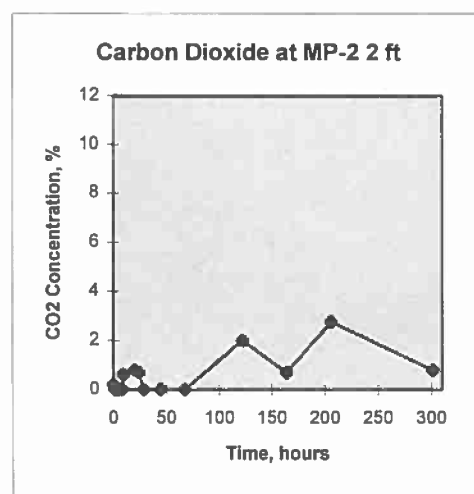
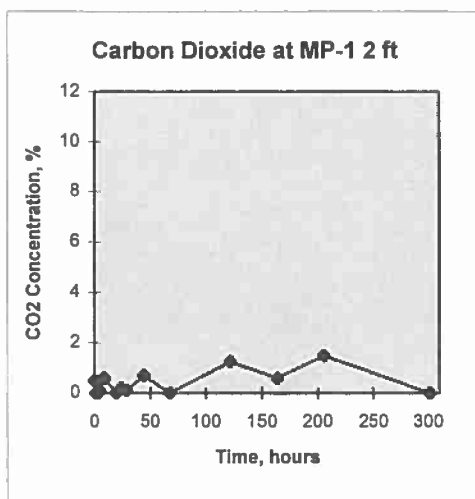
Oxygen at MP-8 4 ft



**In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994**

**CO2 Data**

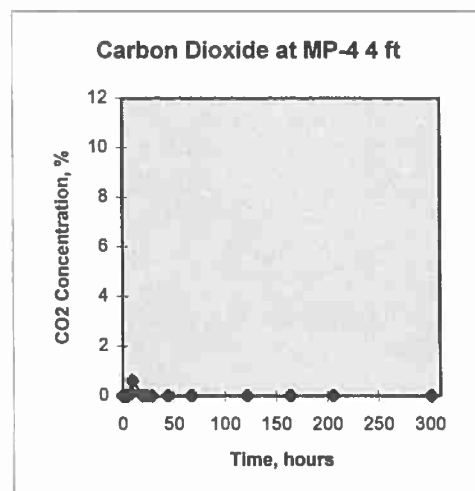
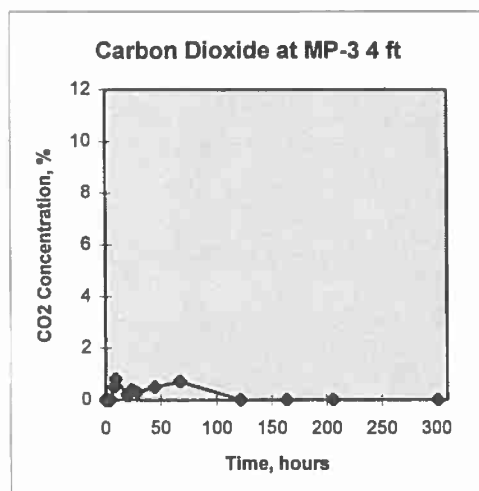
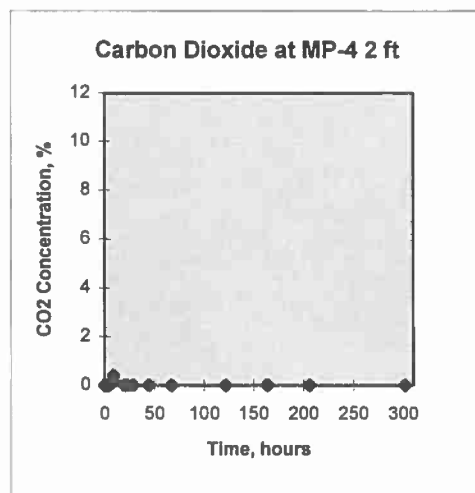
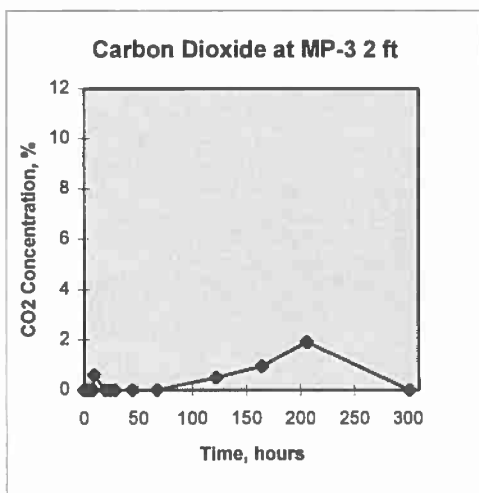
Date	MP -1				MP -2			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	0.5	0	0	0	0.2	0	0
9/20/94	1.5	0	1.5	0.3	1.5	0	1.5	0
9/20/94	3.25	0	3.25	0.6	3.25	0	3.25	0.2
9/20/94	4.5	0.1	4.5	0.7	4.5	0	4.5	0.5
9/20/94	8	0.6	8	1.4	8	0	8	1.2
9/20/94	9.25	0.6	9.25	1.9	9.25	0.6	9.25	0.7
9/21/94	19.75	0	19.75	0.7	19.75	0.8	19.75	0
9/21/94	24	0.2	24	0.7	24	0.7	24	0
9/21/94	28.5	0.1	28.5	0.7	28.5	0	28.5	0.7
9/22/94	44.5	0.7	44.5	0	44.5	0	44.5	0.9
9/23/94	67.5	0	67.5	0.6	67.5	0	67.5	0
9/25/94	122	1.25	122	0	122	2	122	0
9/27/94	164	0.6	164	0	164	0.7	164	0
9/29/94	206	1.5	206	0	206	2.75	206	0
10/3/94	301.5	0	301.5	0	301.5	0.8	301.5	0



**In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994**

**CO2 Data**

Date	MP -3				MP -4			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	0	0	0	0	0	0	0
9/20/94	1.5	0	1.5	0	1.5	0	1.5	0
9/20/94	3.25	0	3.25	0	3.25	0	3.25	0
9/20/94	4.5	0	4.5	0	4.5	0	4.5	0
9/20/94	8	0	8	0.5	8	0.1	8	0.1
9/20/94	9.25	0.6	9.25	0.8	9.25	0.4	9.25	0.6
9/21/94	19.75	0	19.75	0.2	19.75	0	19.75	0
9/21/94	24	0	24	0.4	24	0	24	0
9/21/94	28.5	0	28.5	0.3	28.5	0	28.5	0
9/22/94	44.5	0	44.5	0.5	44.5	0	44.5	0
9/23/94	67.5	0	67.5	0.7	67.5	0	67.5	0
9/25/94	122	0.5	122	0	122	0	122	0
9/27/94	164	0.95	164	0	164	0	164	0
9/29/94	206	1.9	206	0	206	0	206	0
10/3/94	301.5	0	301.5	0	301.5	0	301.5	0





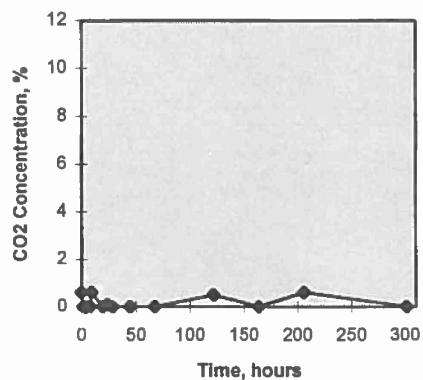
**In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994**

**CO2 Data**

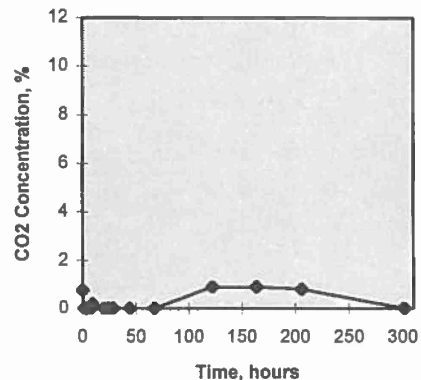
Date	MP -5			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	0.6	0	0
9/20/94	1.5	0	1.5	0.5
9/20/94	3.25	0	3.25	0.2
9/20/94	4.5	0	4.5	0.6
9/20/94	8	0	8	0.7
9/20/94	9.25	0.6	9.25	0.9
9/21/94	19.75	0	19.75	0.2
9/21/94	24	0.1	24	0.3
9/21/94	28.5	0	28.5	0.2
9/22/94	44.5	0	44.5	0.2
9/23/94	67.5	0	67.5	0.1
9/25/94	122	0.5	122	0
9/27/94	164	0	164	0.5
9/29/94	206	0.6	206	0
10/3/94	301.5	0	301.5	0

MP -6			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	0.75	0	0
1.5	0	1.5	0
3.25	0	3.25	0.7
4.5	0	4.5	0.8
8	0	8	0.9
9.25	0.2	9.25	1.5
19.75	0	19.75	0.8
24	0	24	0.9
28.5	0	28.5	0.9
44.5	0	44.5	0.9
67.5	0	67.5	0.8
122	0.9	122	0
164	0.9	164	0
206	0.8	206	0
301.5	0	301.5	0

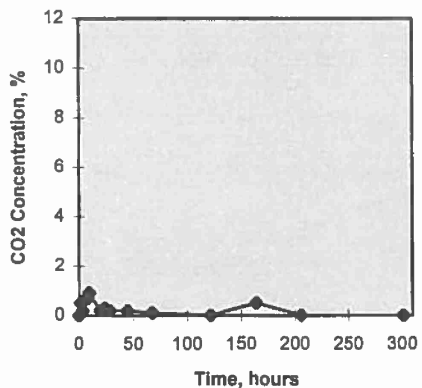
**Carbon Dioxide at MP-5 2 ft**



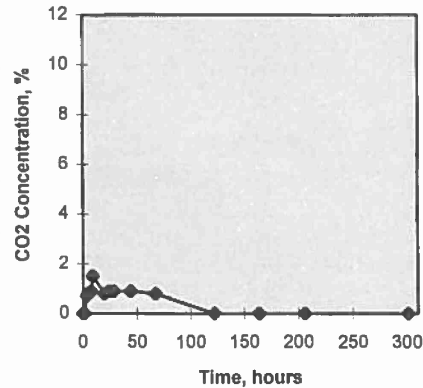
**Carbon Dioxide at MP-6 2 ft**



**Carbon Dioxide at MP-5 4 ft**



**Carbon Dioxide at MP-6 4 ft**

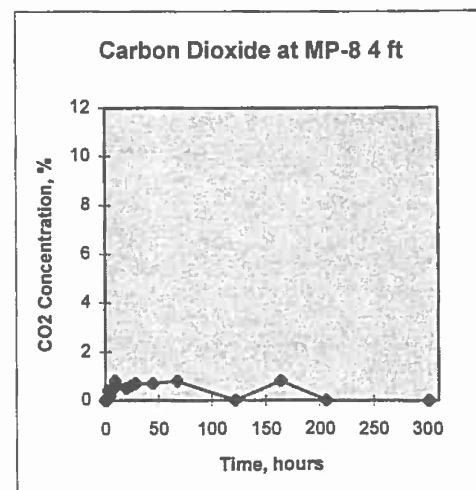
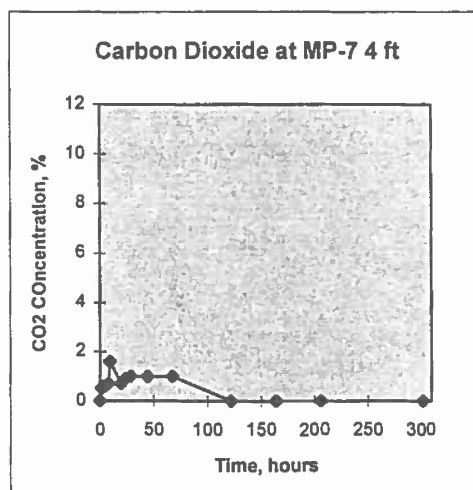
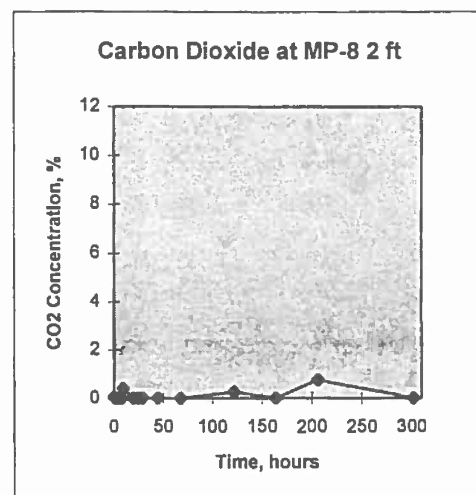
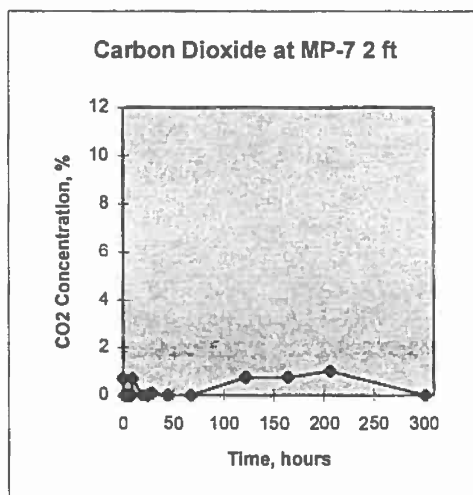


In Situ Respiration Data for Tyndall Air Force Base  
Test #1  
September 20 through October 3, 1994

CO2 Data

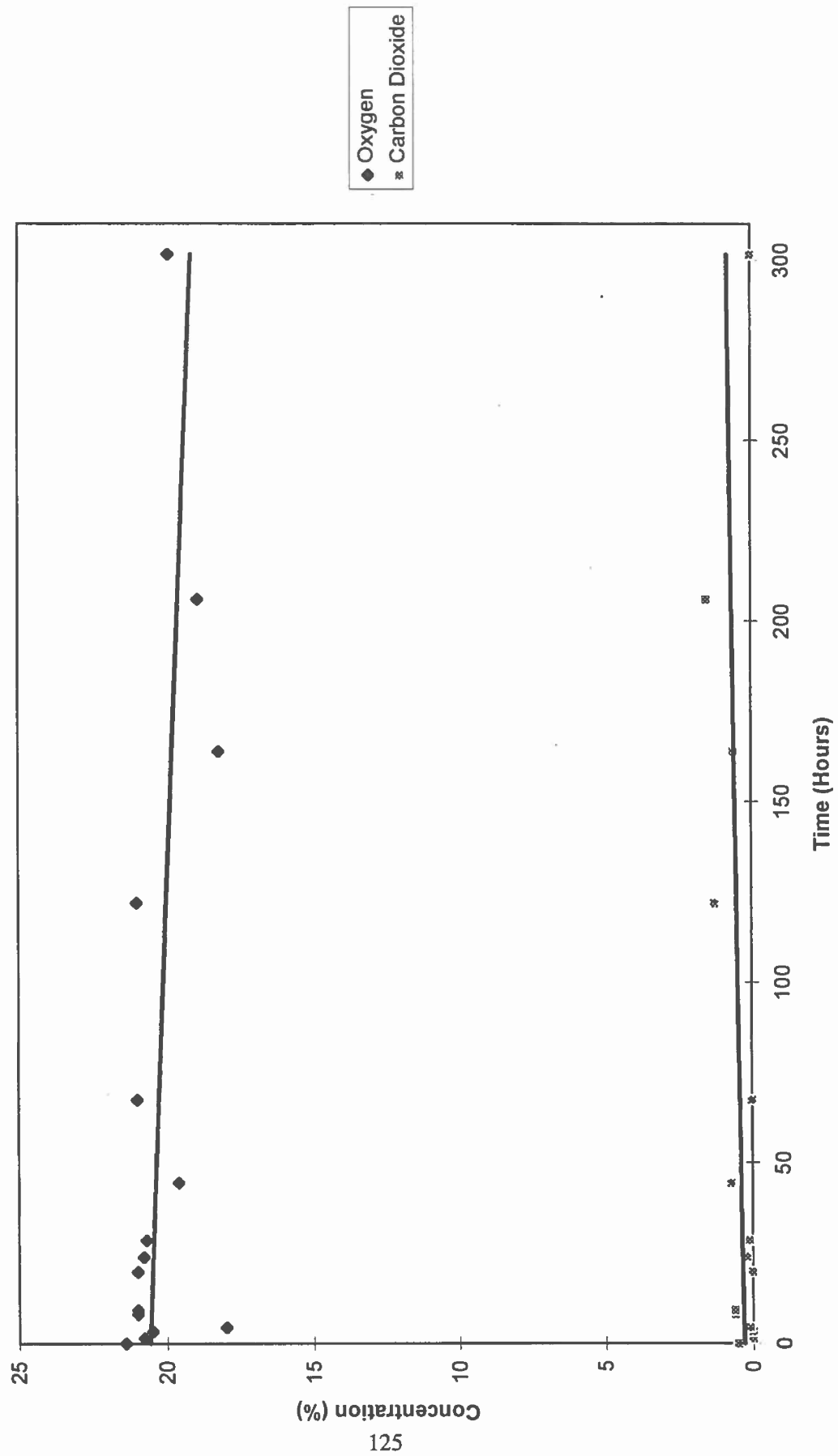
Date	MP -7			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
9/20/94	0	0.7	0	0
9/20/94	1.5	0	1.5	0.5
9/20/94	3.25	0	3.25	0.6
9/20/94	4.5	0	4.5	0.6
9/20/94	8	0	8	0.7
9/20/94	9.25	0.7	9.25	1.6
9/21/94	19.75	0	19.75	0.7
9/21/94	24	0	24	0.9
9/21/94	28.5	0.1	28.5	1
9/22/94	44.5	0	44.5	1
9/23/94	67.5	0	67.5	1
9/25/94	122	0.75	122	0
9/27/94	164	0.75	164	0
9/29/94	206	1	206	0
10/3/94	301.5	0	301.5	0

MP -8			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	0.05	0	0
1.5	0	1.5	0
3.25	0	3.25	0.4
4.5	0	4.5	0.2
8	0	8	0.5
9.25	0.4	9.25	0.8
19.75	0	19.75	0.5
24	0	24	0.6
28.5	0	28.5	0.7
44.5	0	44.5	0.7
67.5	0	67.5	0.8
122	0.25	122	0
164	0	164	0.8
206	0.75	206	0
301.5	0	301.5	0

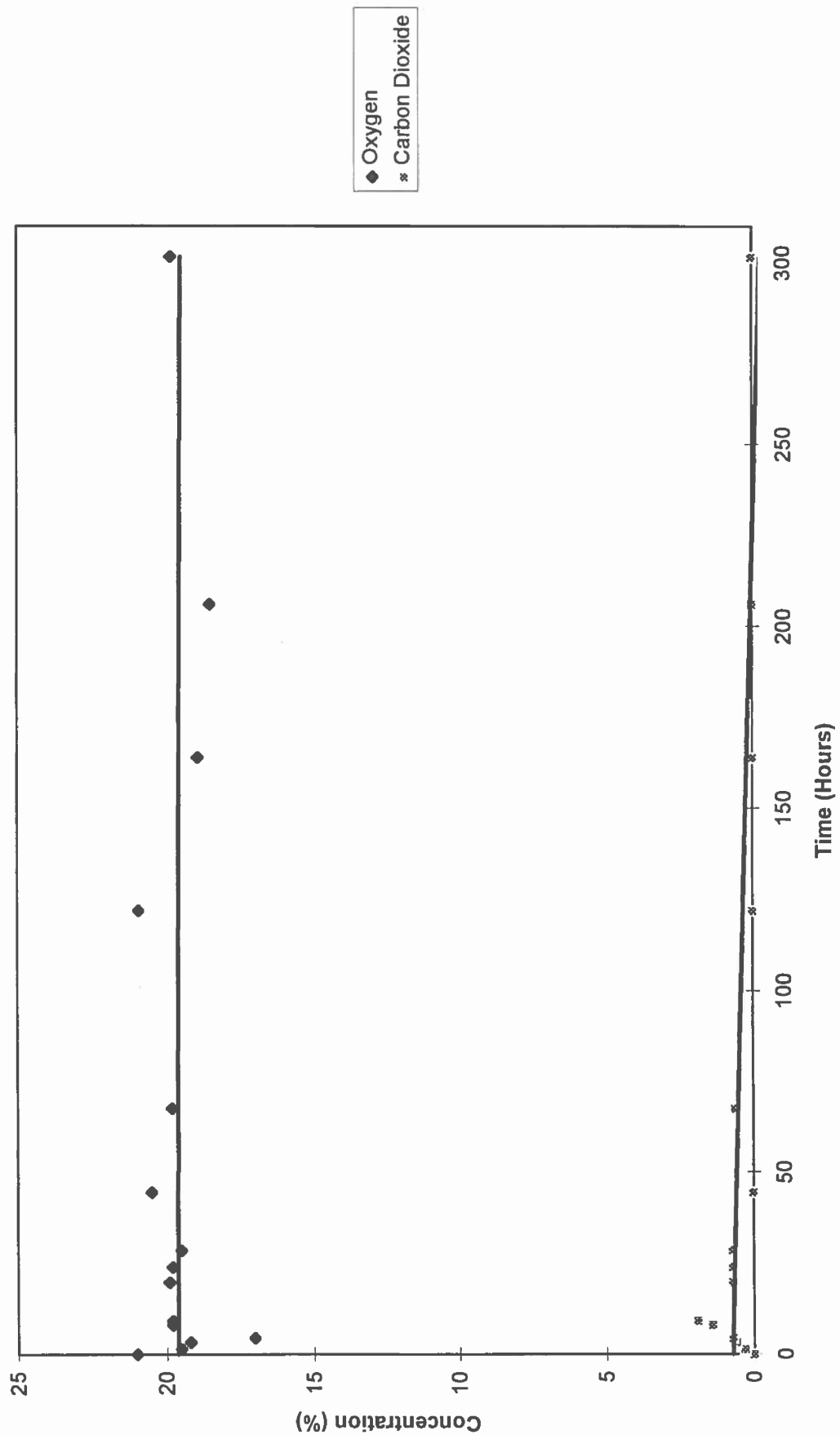


SUMMARY OUTPUT		Respiration Test #1							
		MP-1 @ 2 feet							
Regression Statistics									
Multiple R	0.405810304								
R Square	0.164682003								
Adjusted R Square	0.100426773								
Standard Error	1.033941821								
Observations	15								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	2.739889379	2.739869	2.562935	0.133405467				
Residual	13	13.89746395	1.069036						
Total	14	16.63733333							
		Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.000%	Upper 95.000%	
Intercept	20.57817684	0.335232354	61.36812	2.11E-17	19.85375451	21.3025992	19.85375451	21.30259916	
X Variable 1	-0.004852031	0.003030783	-1.600917	0.133405	-0.011399638	0.00169557	-0.011399638	0.001695575	
SUMMARY OUTPUT		Respiration Test #1							
		MP-1 @ 4 feet							
Regression Statistics									
Multiple R	0.051333598								
R Square	0.002635138								
Adjusted R Square	-0.074085236								
Standard Error	1.013525856								
Observations	15								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	0.035282745	0.035283	0.034347	0.855830269				
Residual	13	13.35405059	1.027235						
Total	14	13.38933333							
		Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.000%	Upper 95.000%	
Intercept	19.63019631	0.328702322	59.72028	3.01E-17	18.92007826	20.3403144	18.92007826	20.34031437	
X Variable 1	-0.000550605	0.002970937	-0.18533	0.85583	-0.006968924	0.00586771	-0.006968924	0.005867714	

Oxygen and Carbon Dioxide at MP-1 at 2 Feet  
September 20 through October 3, 1994

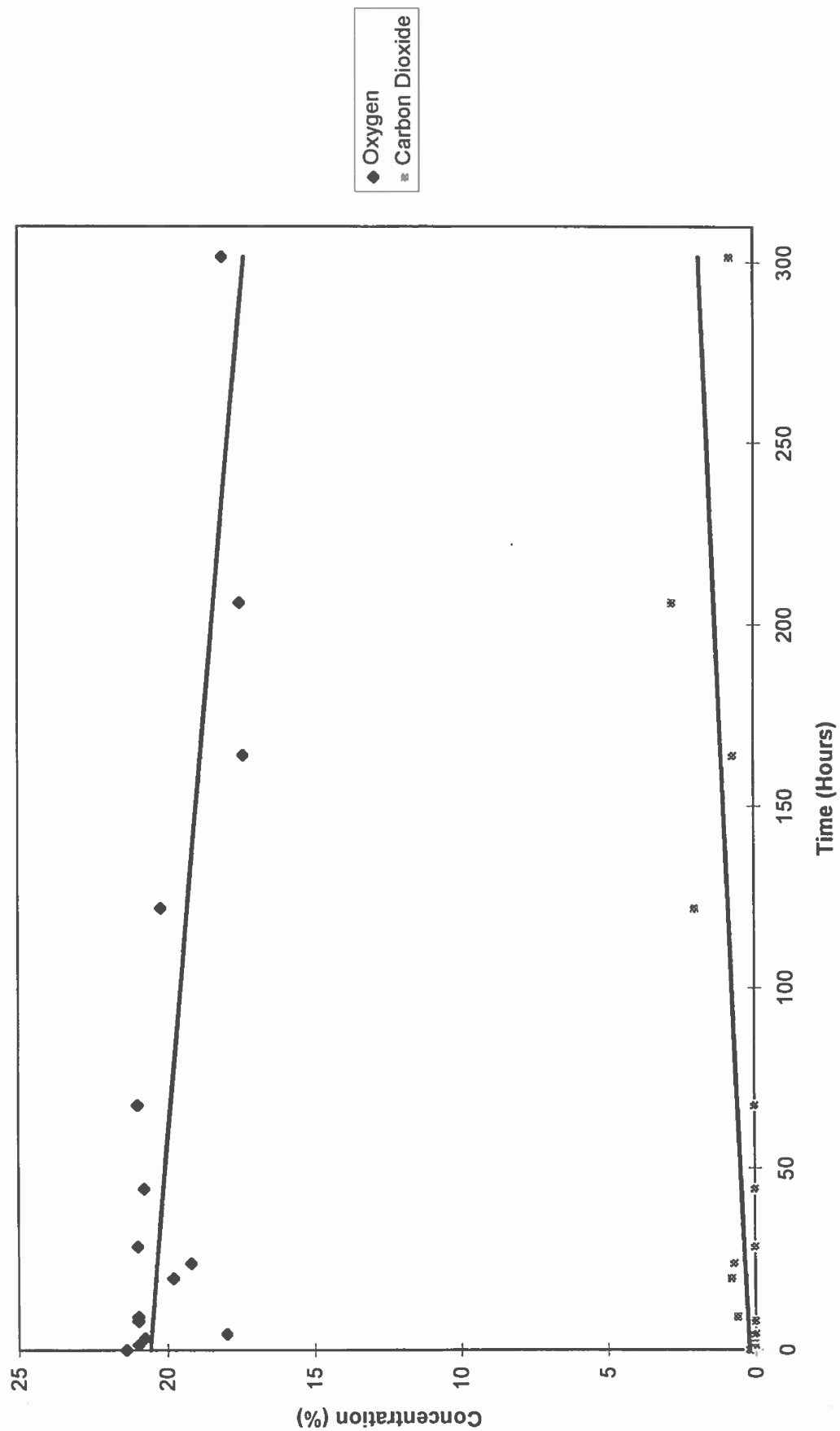


Oxygen and Carbon Dioxide at MP-1 at 4 Feet  
September 20 through October 3, 1994

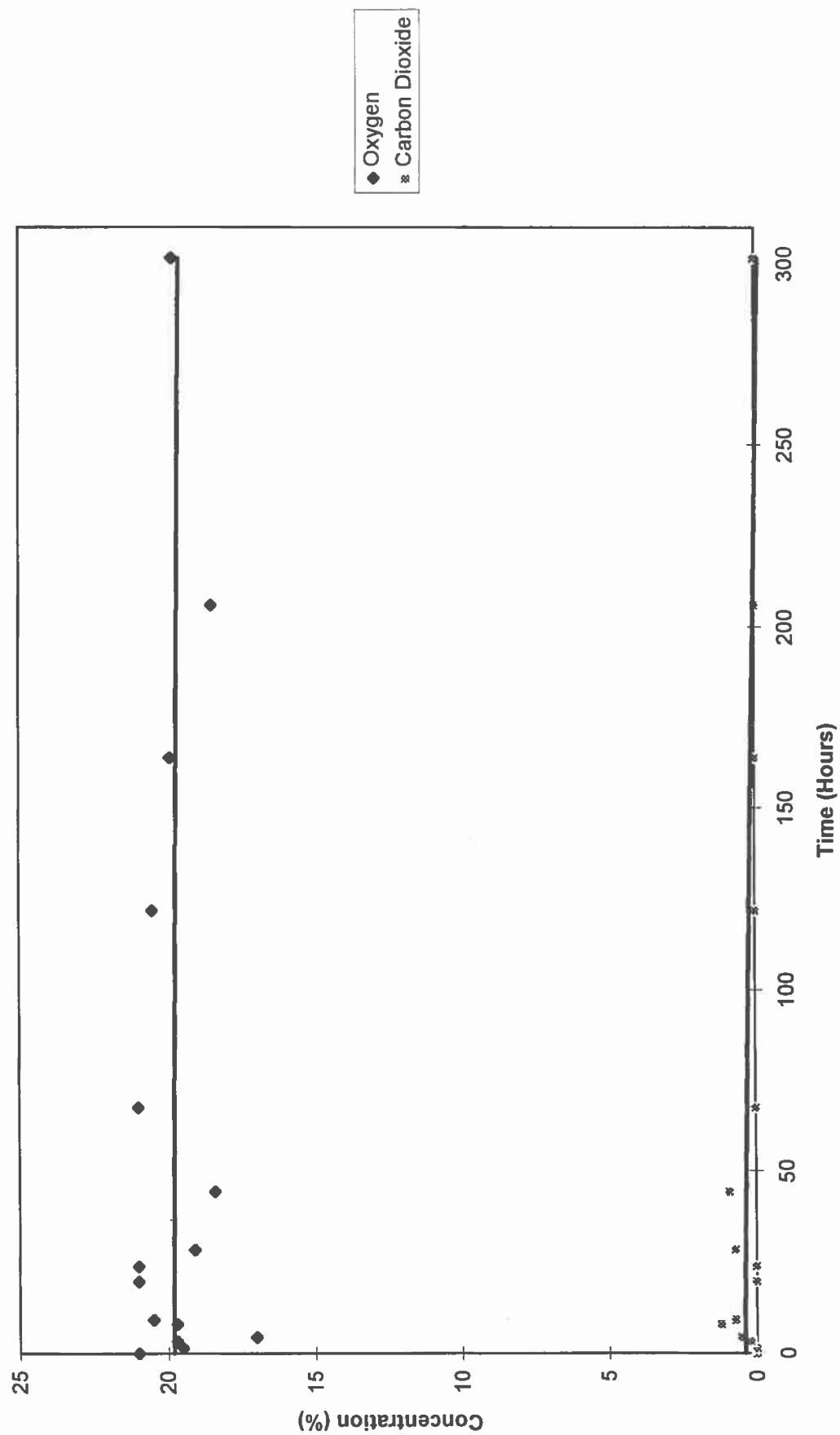


SUMMARY OUTPUT				Respiration Test #1			
				MP-2 @ 2 feet			
Regression Statistics							
Multiple R	0.675388297						
R Square	0.456149351						
Adjusted R Square	0.414314686						
Standard Error	1.108347018						
Observations	15						
ANOVA							
	df	SS	MS	F	Significance F		
Regression	1	13.39436955	13.3943695	10.90362	0.005724949		
Residual	13	15.96963045	1.22843311				
Total	14	29.364					
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Upper 95.000%
Intercept	20.59824134	0.359454311	57.3041989	5.13E-17	19.82168766	21.374795	21.37479502
X Variable 1	-0.010728026	0.003248886	-3.3020632	0.005725	-0.017746815	-0.0037092	-0.003709236
SUMMARY OUTPUT				Respiration Test #1			
				MP-2 @ 4 feet			
Regression Statistics							
Multiple R	0.064627444						
R Square	0.004176707						
Adjusted R Square	-0.072425085						
Standard Error	1.20098321						
Observations	15						
ANOVA							
	df	SS	MS	F	Significance F		
Regression	1	0.078644599	0.0786446	0.054525	0.819005411		
Residual	13	18.75068873	1.44236067				
Total	14	18.82933333					
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Upper 95.000%
Intercept	19.82836893	0.389497681	50.9075404	2.38E-16	18.98691052	20.6698274	20.66982735
X Variable 1	-0.00082204	0.003520429	-0.2335057	0.819005	-0.008427464	0.00678338	0.006783383

Oxygen and Carbon Dioxide at MP-2 at 2 Feet  
September 20 through October 3, 1994



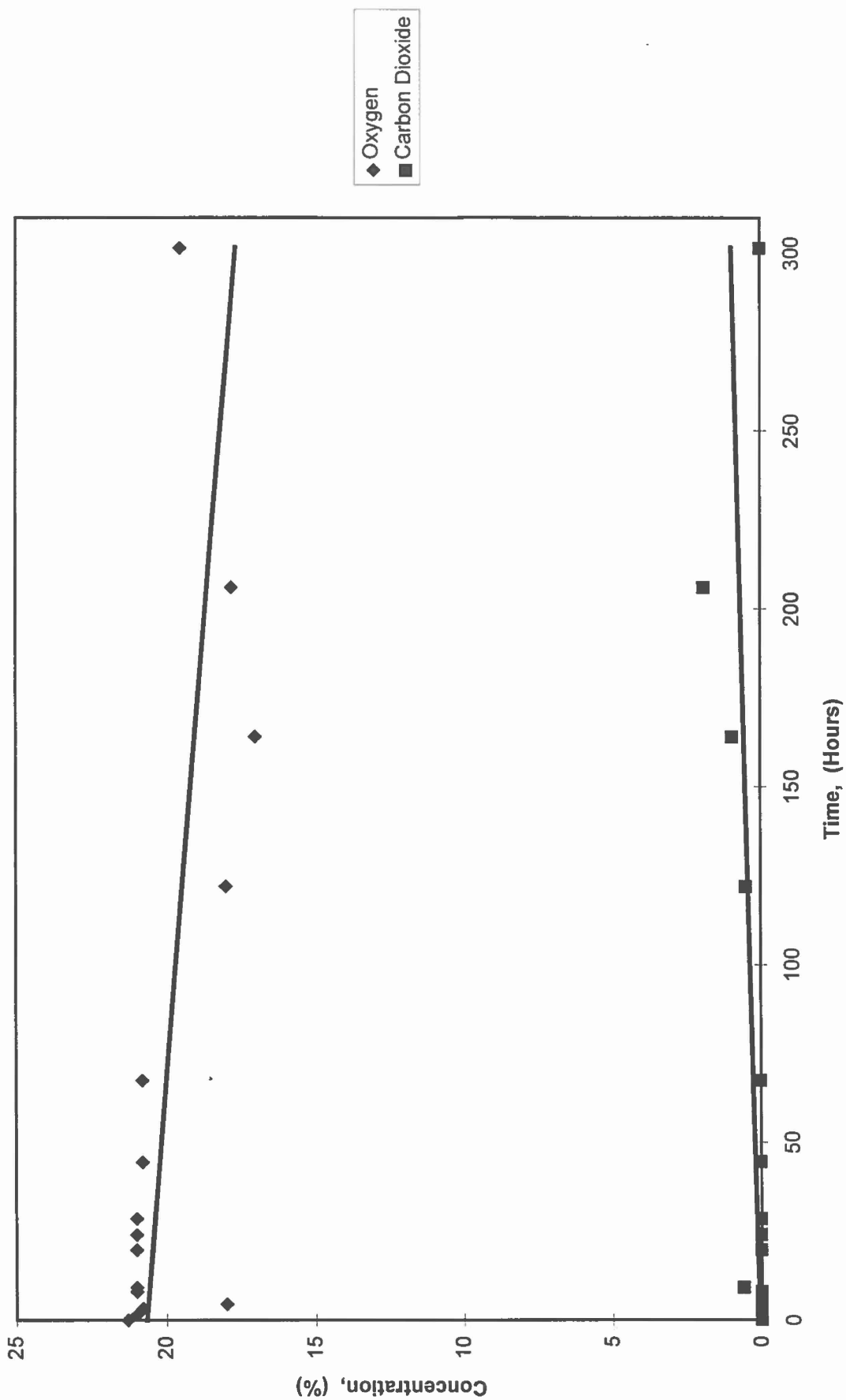
Oxygen and Carbon Dioxide at MP-2 at 4 Feet  
September 20 through October 3, 1994



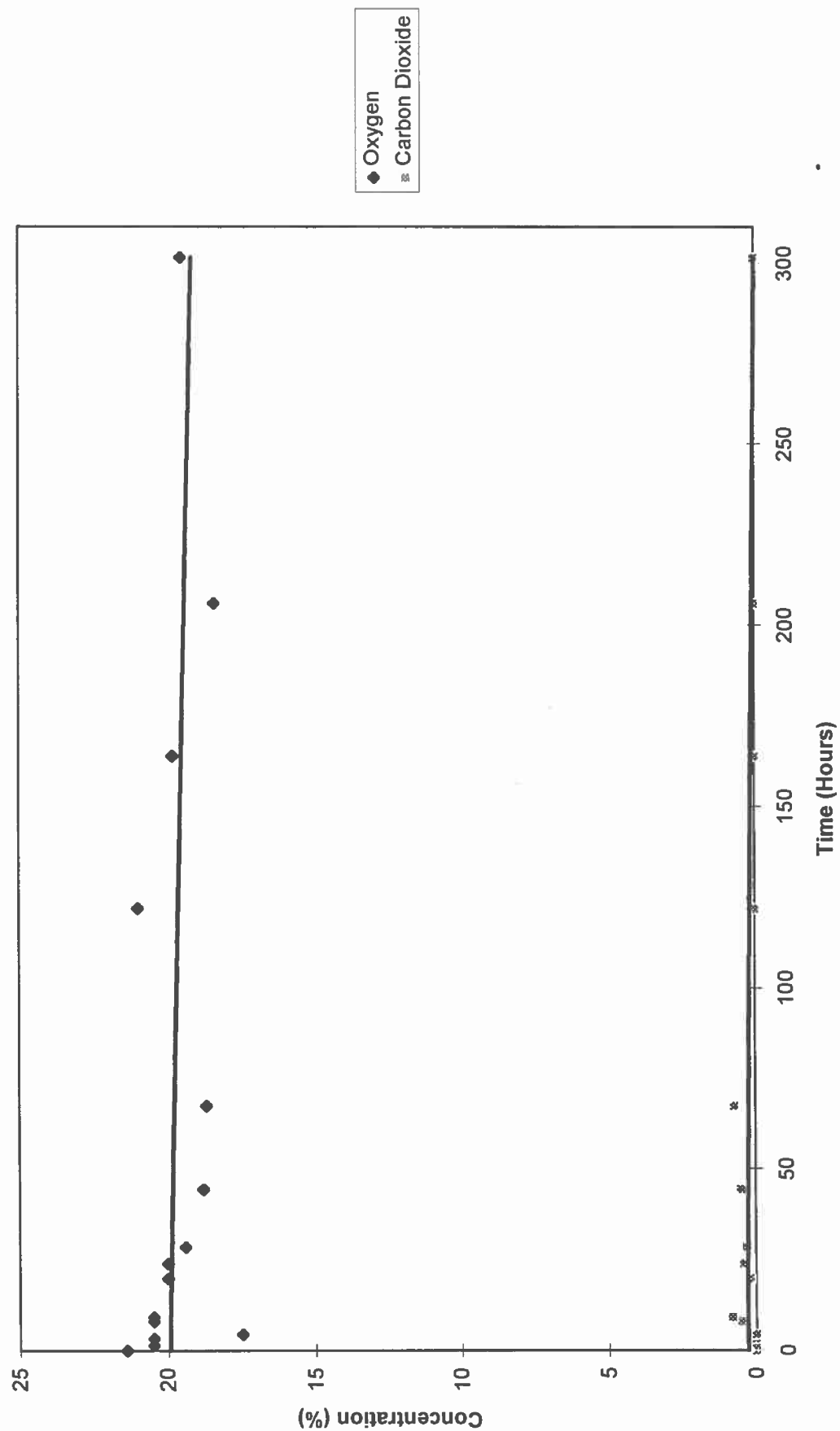




Oxygen and Carbon Dioxide at MP-3 at 2 Feet  
September 20 through October 3, 1994

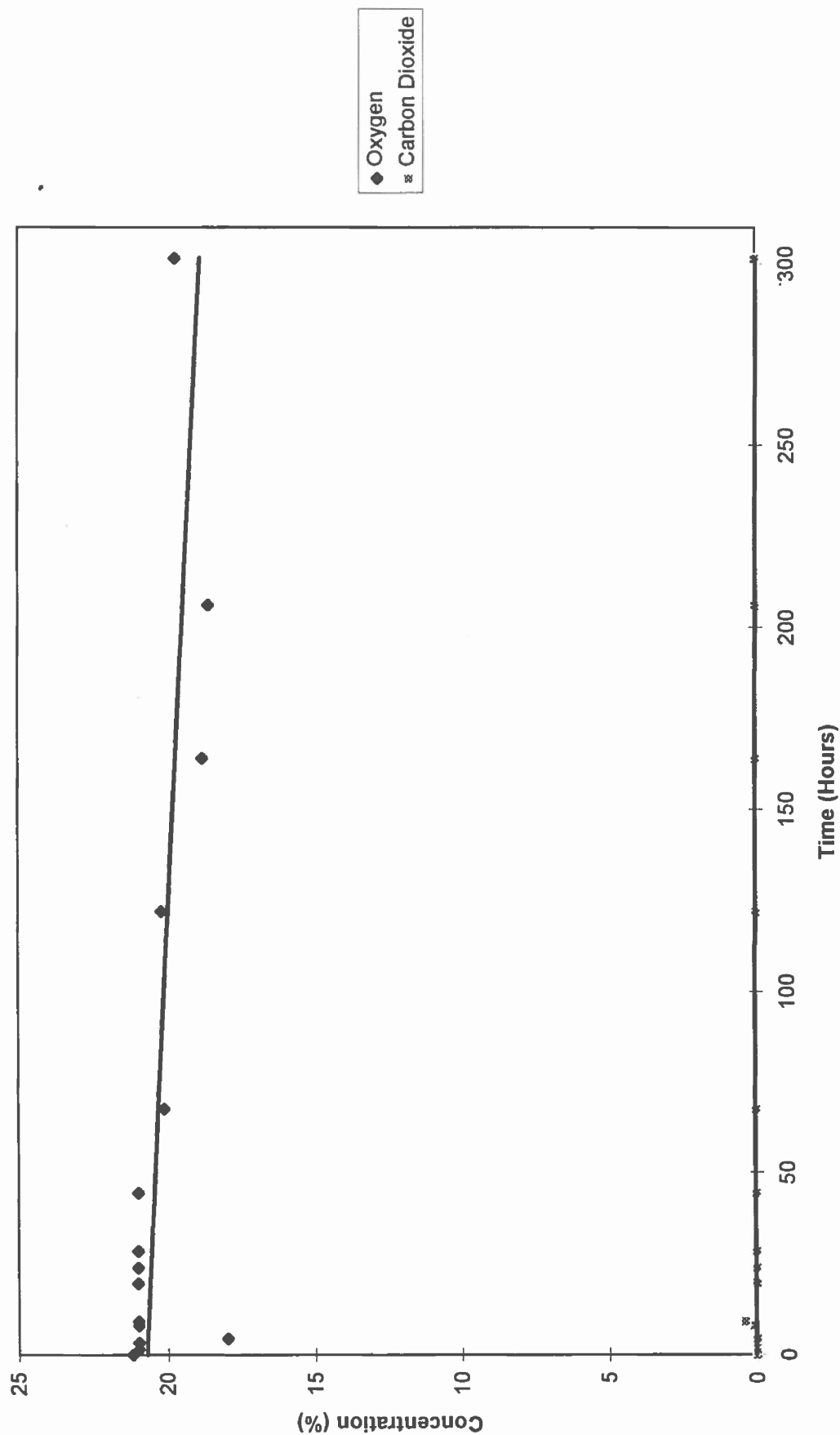


Oxygen and Carbon Dioxide at MP-3 at 4 Feet  
September 20 through October 3, 1994

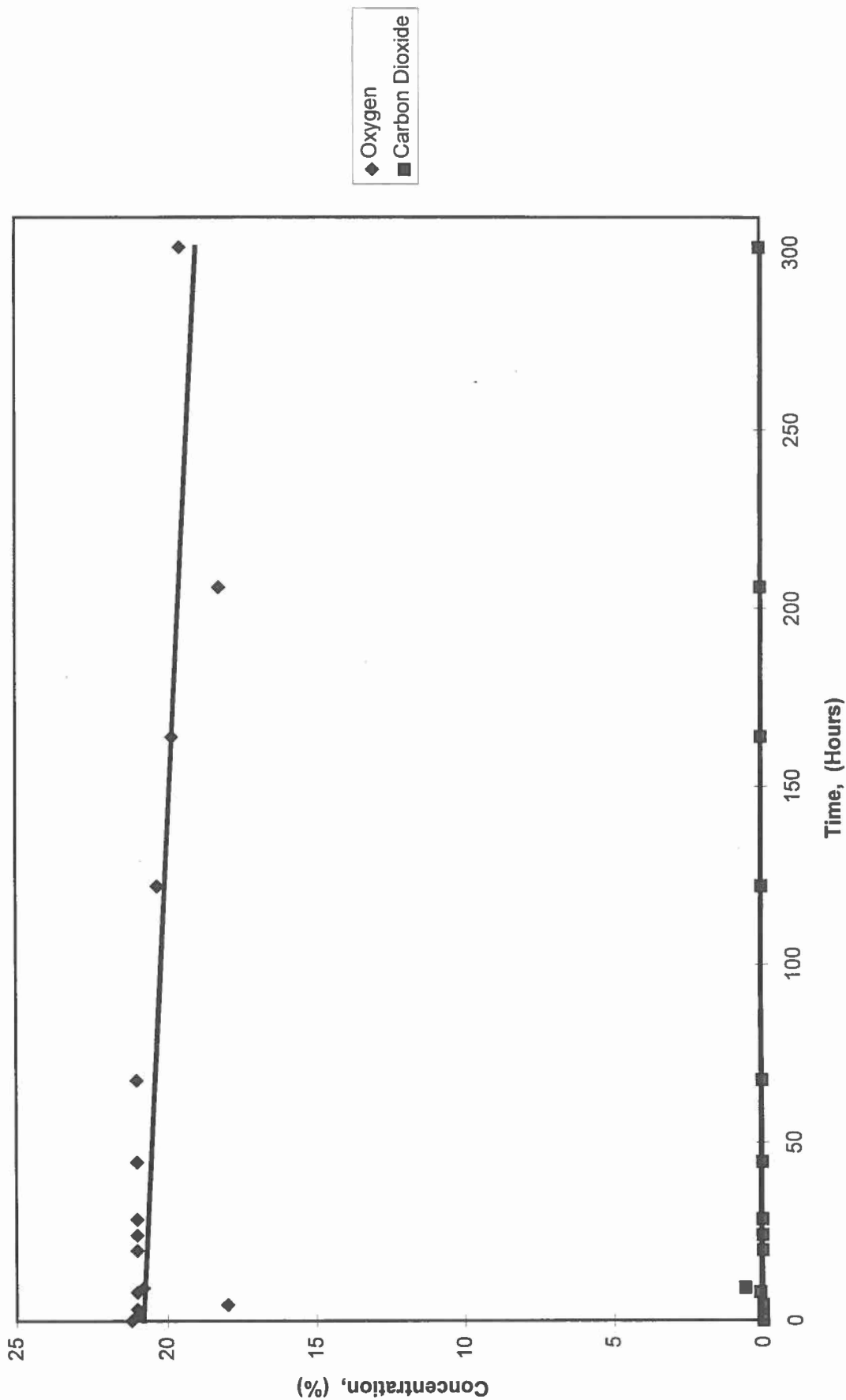




Oxygen and Carbon Dioxide at MP-4 at 2 Feet  
September 20 through October 3, 1994

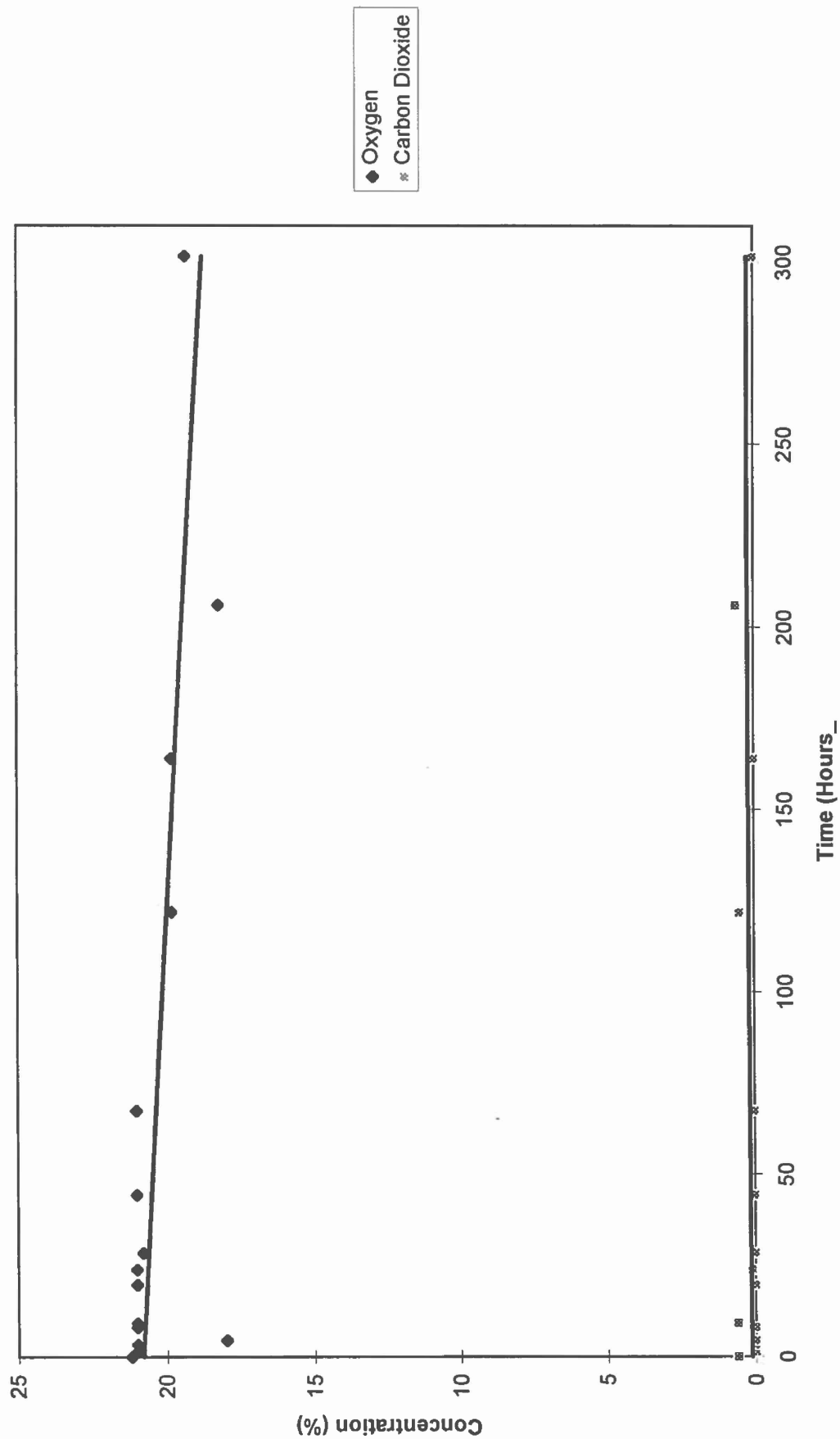


Oxygen and Carbon Dioxide at MP-4 at 4 Feet  
September 20 through October 3, 1994



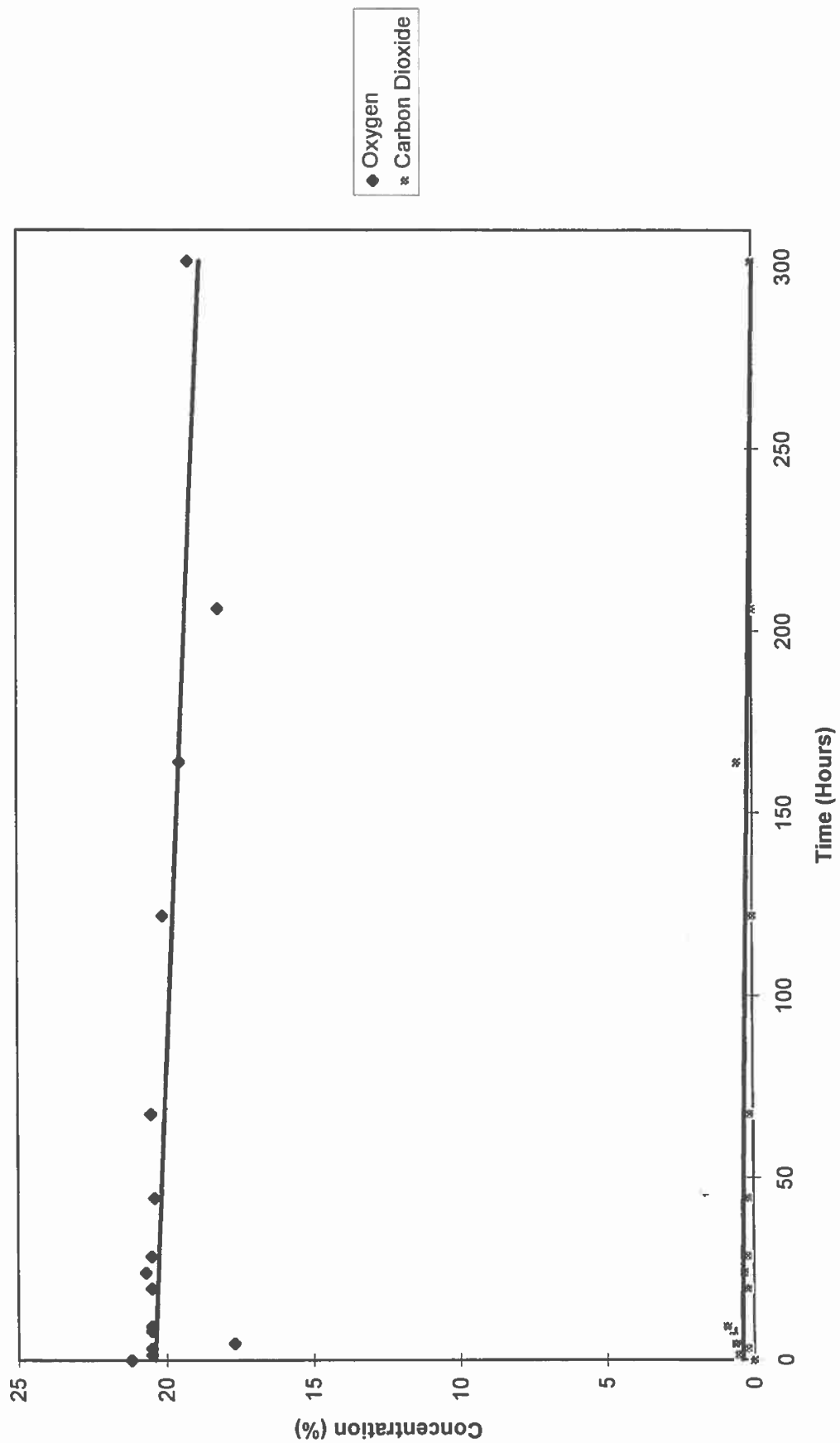


Oxygen and Carbon Dioxide at MP-5 at 2 Feet  
January 9 through 23, 1995



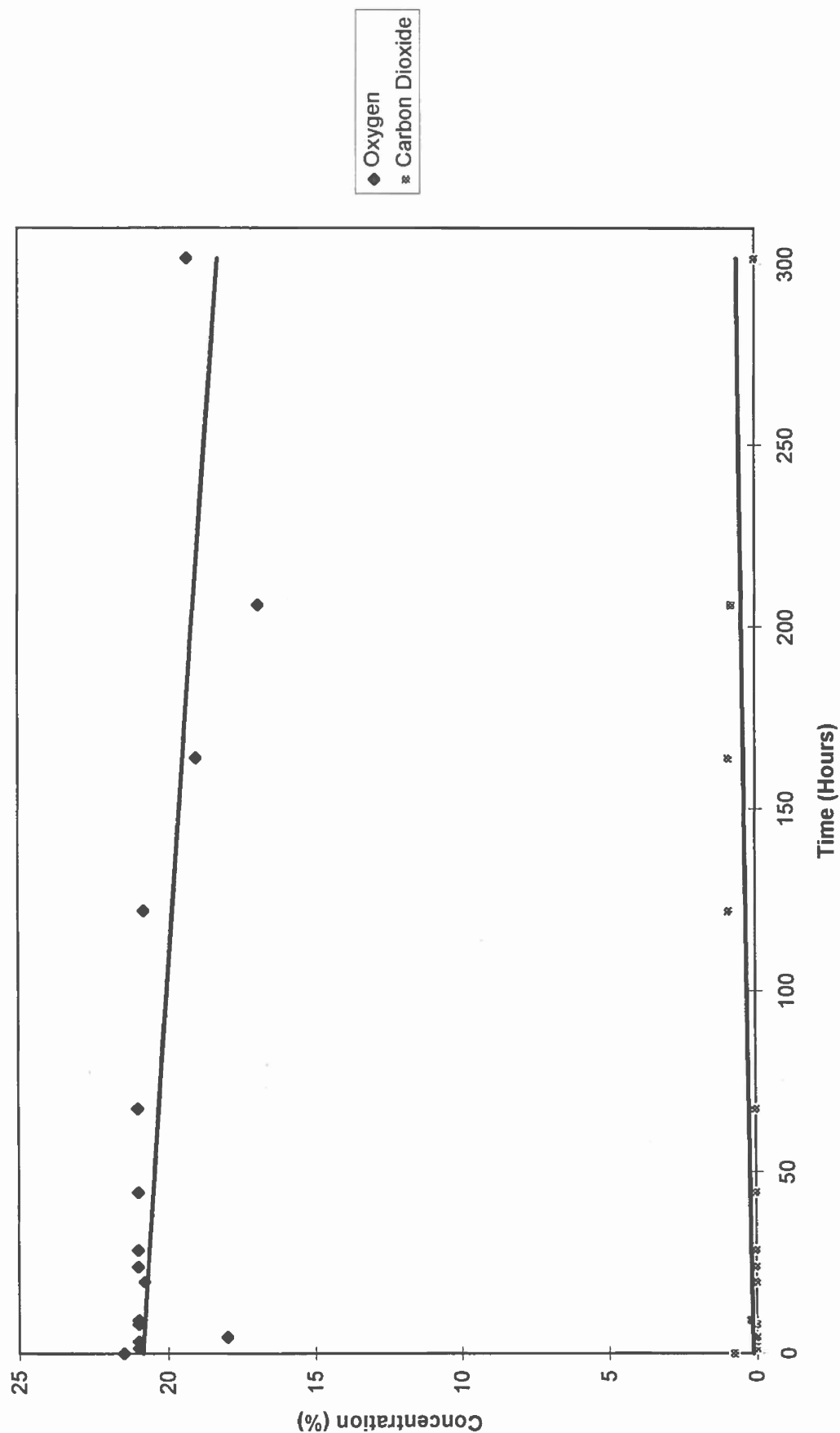


Oxygen and Carbon Dioxide at MP-5 at 4 Feet  
September 20 through October 3, 1994

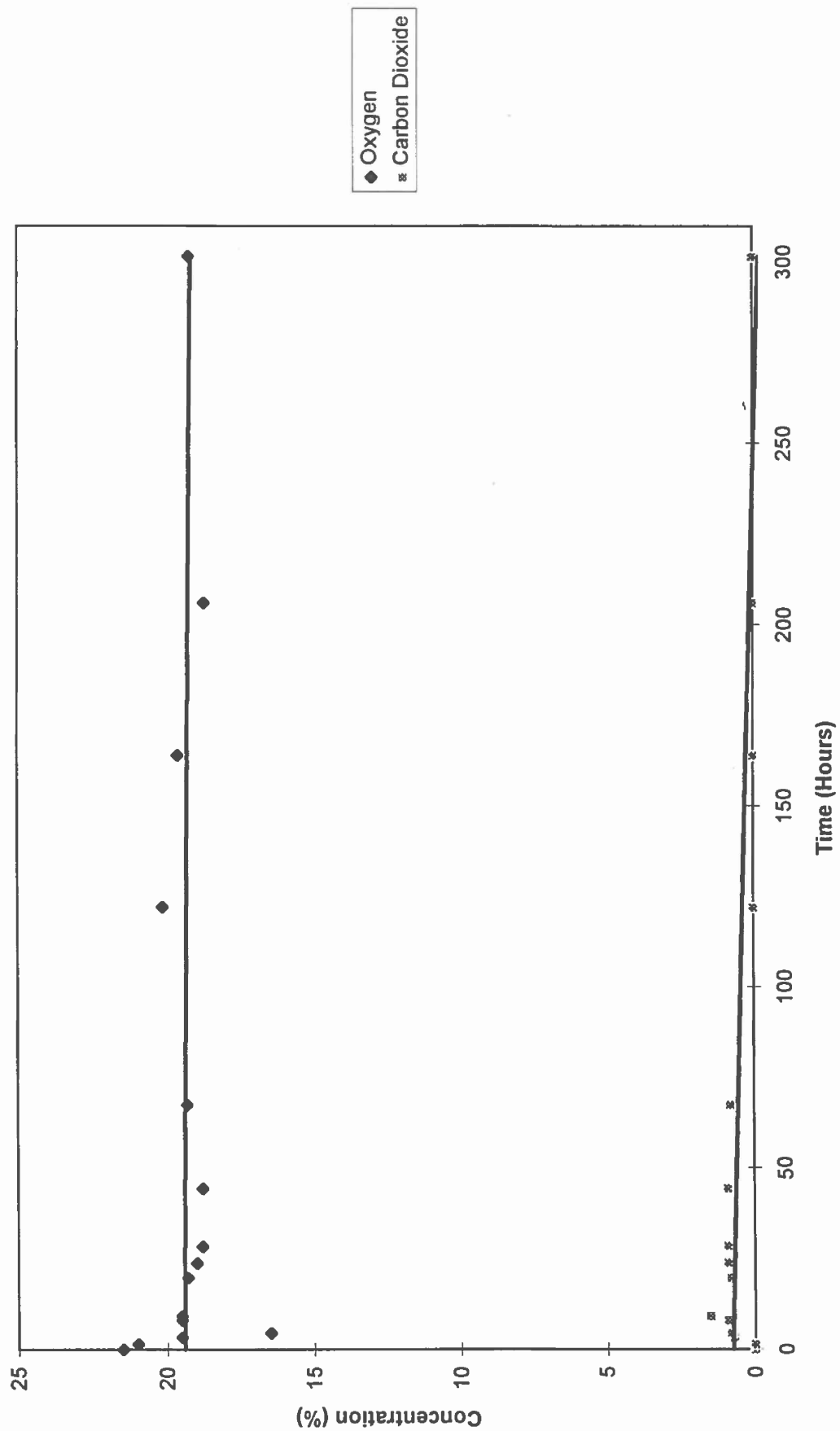




Oxygen and Carbon Dioxide at MP-6 at 2 Feet  
September 20 through October 3, 1994

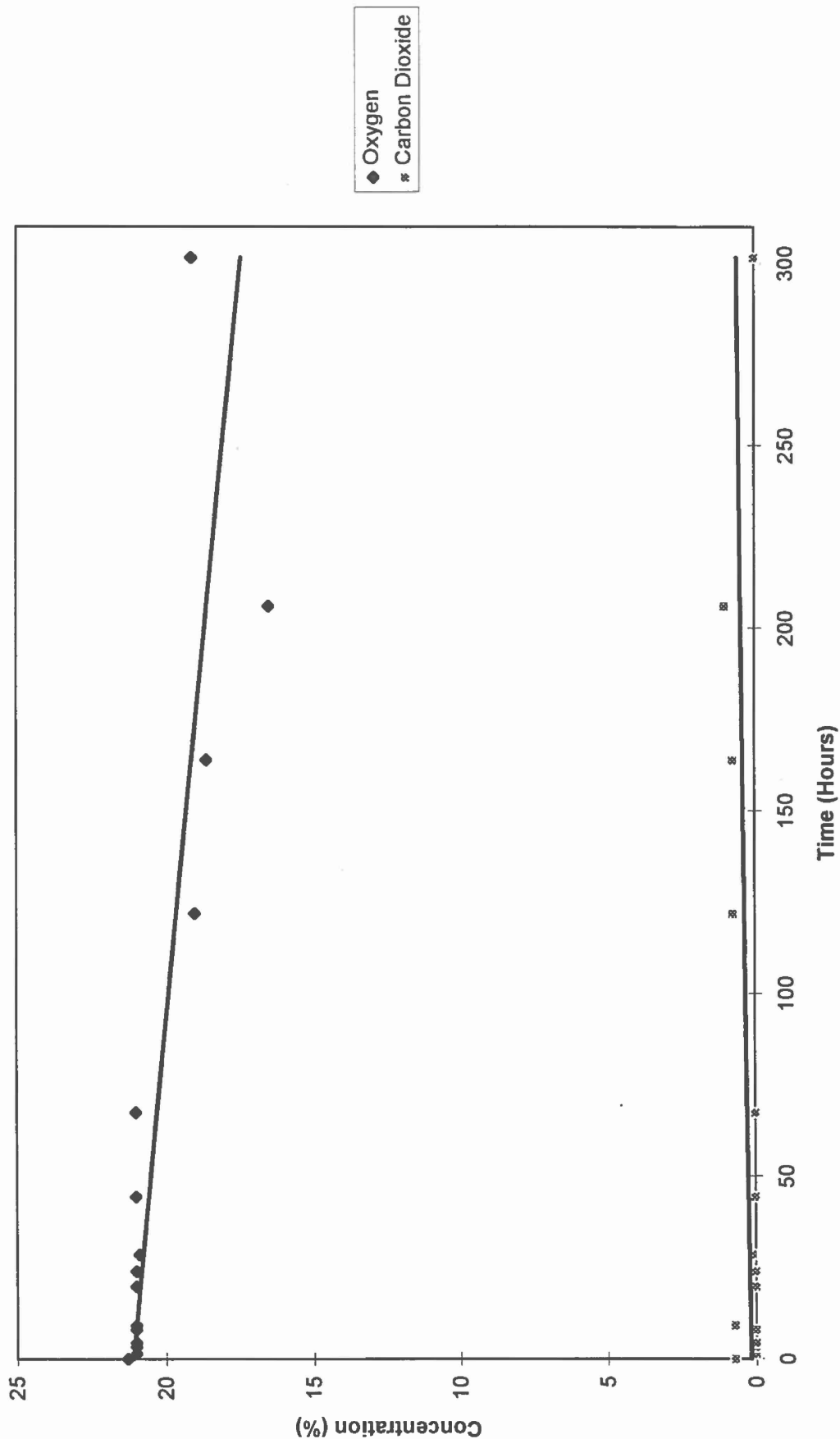


Oxygen and Carbon Dioxide at MP-6 at 4 Feet  
September 20 through October 3, 1994

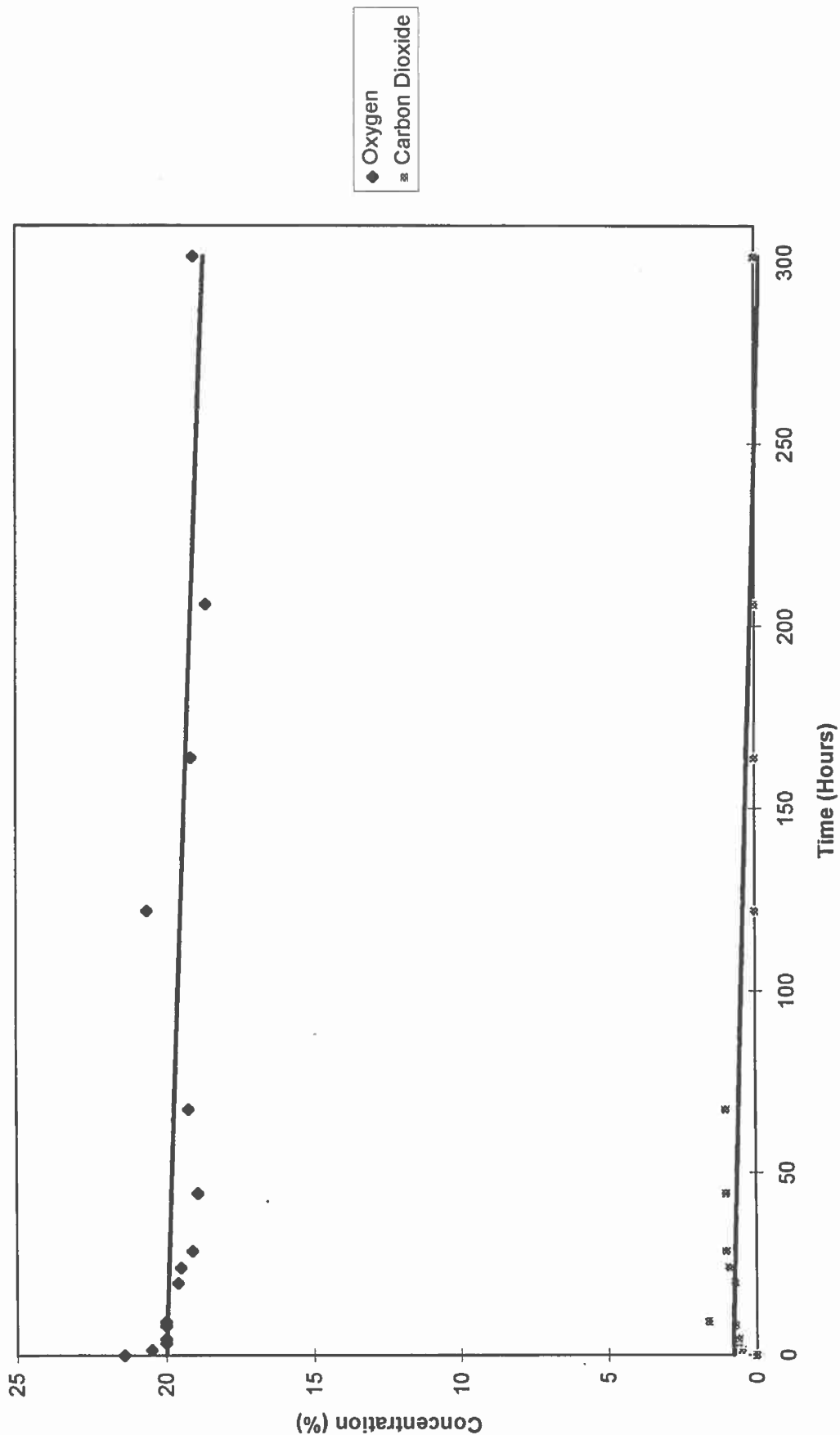




Oxygen and Carbon Dioxide at MP-7 at 2 Feet  
January 9 through 23, 1995



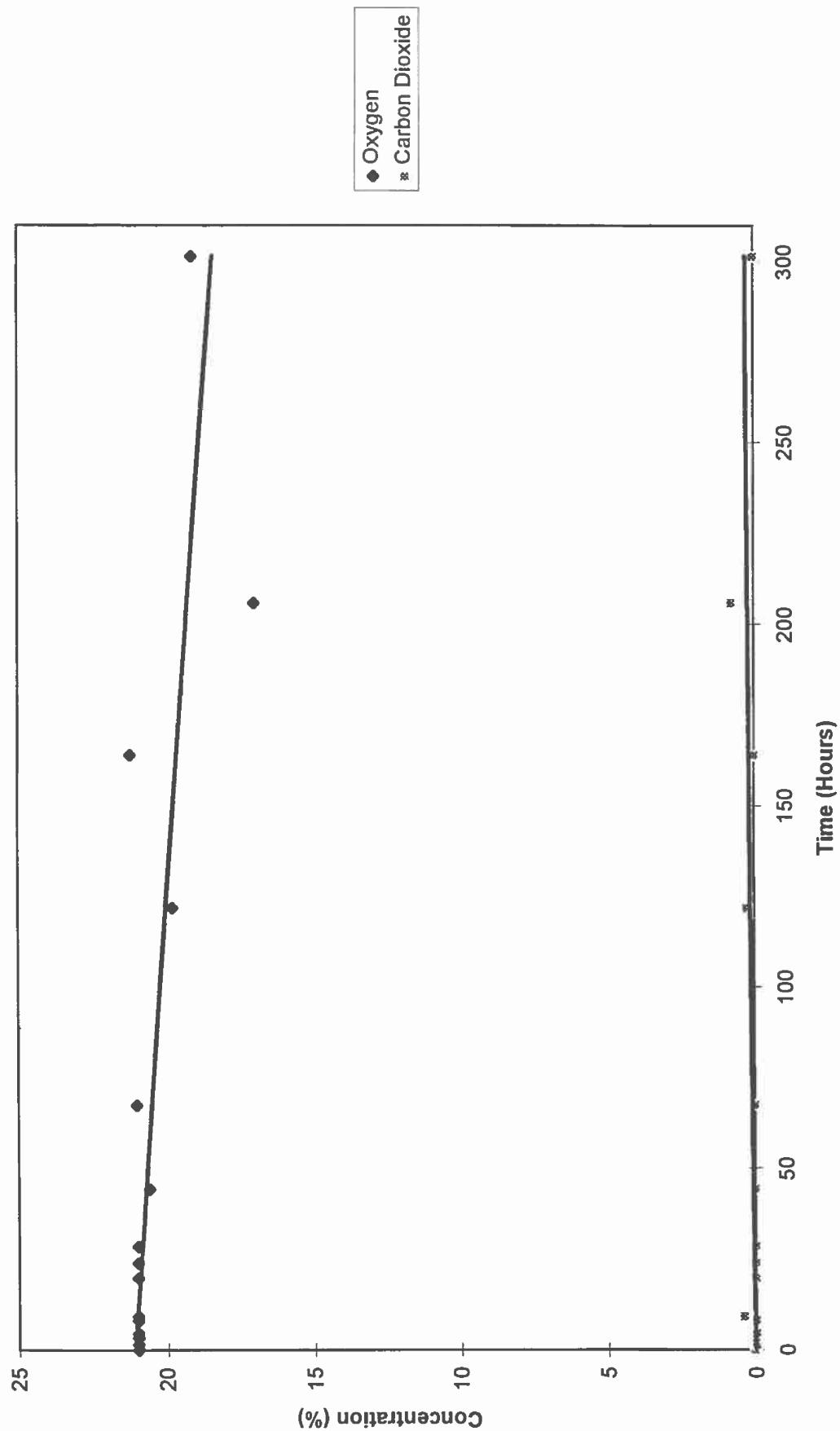
Oxygen and Carbon Dioxide at MP-7 at 4 Feet  
September 20 through October 3, 1994



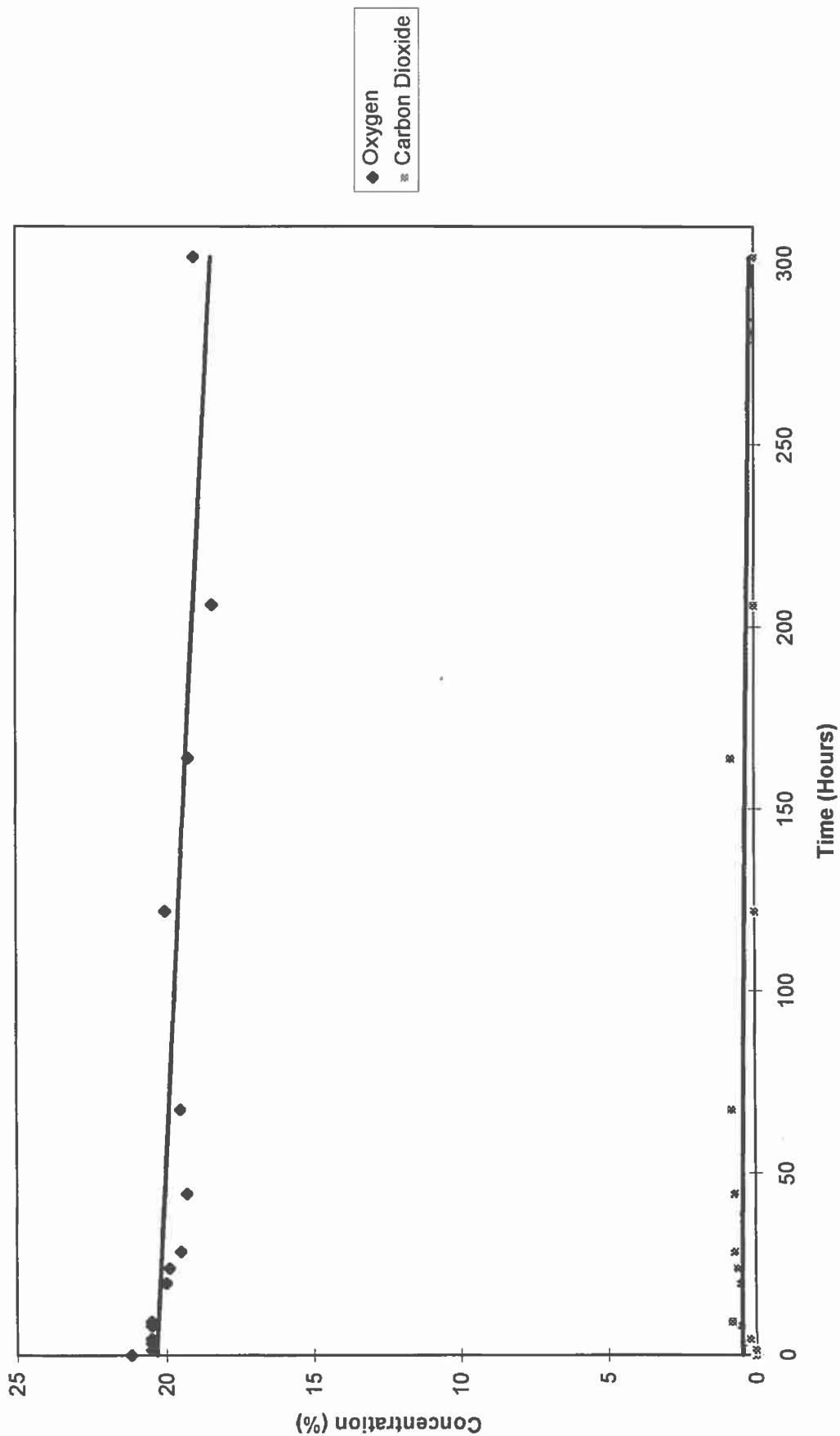




Oxygen and Carbon Dioxide at MP-8 at 2 Feet  
September 20 through October 3, 1994



# Oxygen and Carbon Dioxide at MP-8 at 4 Feet September 20 through October 3, 1994



## **APPENDIX B**

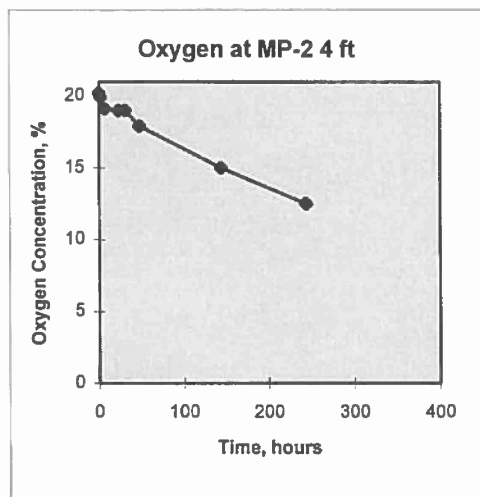
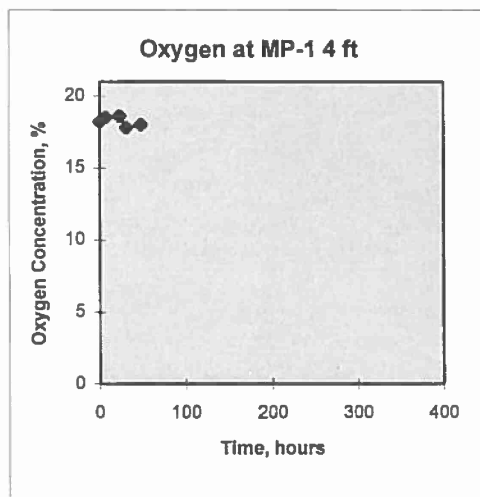
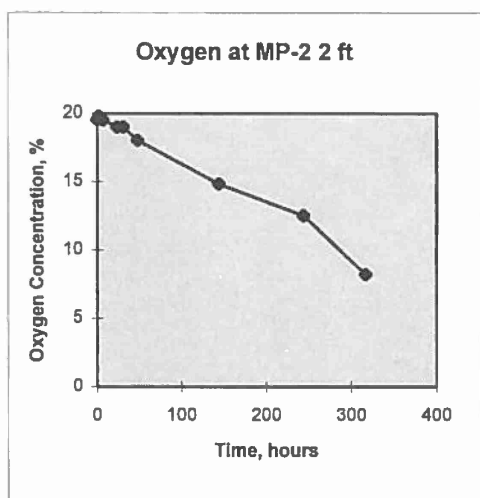
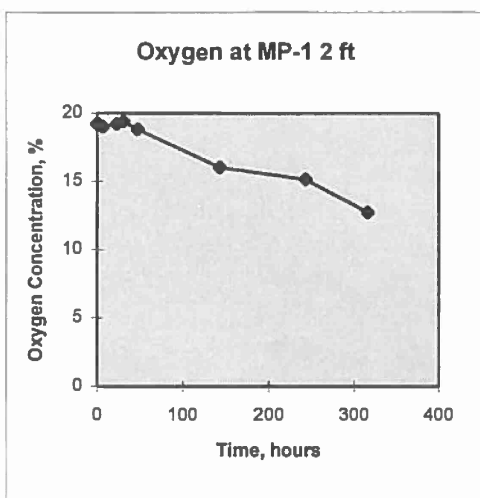
### **OXYGEN AND CARBON DIOXIDE DATA AND REGRESSION ANALYSIS OUTPUT FOR RESPIRATION TEST 2**

**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

**Oxygen Data**

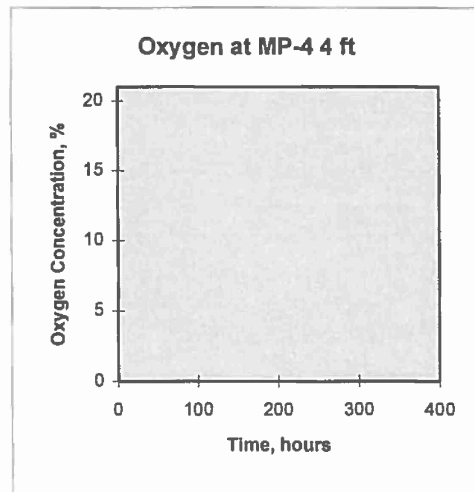
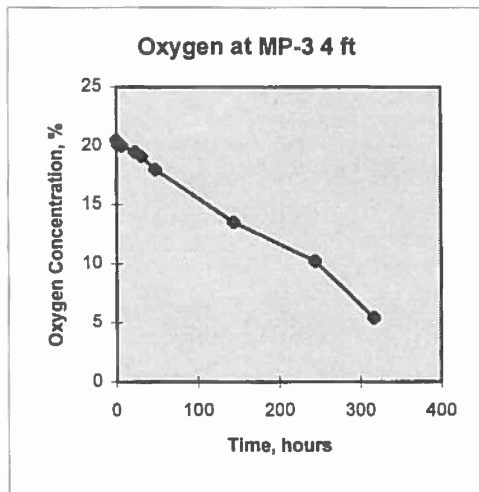
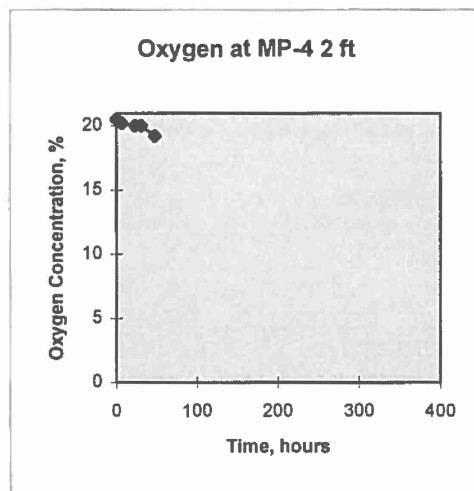
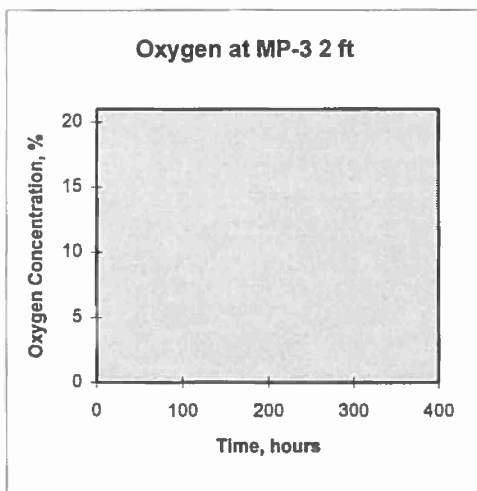
MP -1				
Date	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0	19.2	0	18.2
1/11/95	2	19.2	2	18.3
1/11/95	7	19	7	18.5
1/12/95	23.25	19.2	23.25	18.6
1/12/95	31	19.4	31	17.8
1/13/95	48	18.8	48	18
1/17/95	144	16	144	
1/21/95	244	15.1	244	
1/24/95	317	12.7	317	

MP -2			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	19.5	0	20.2
2	19.8	2	19.9
7	19.5	7	19.1
23.25	19	23.25	19
31	19	31	19
48	18	48	17.9
144	14.8	144	15
244	12.5	244	12.5
317	8.2	317	



**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

MP -3			MP -4		
Oxygen Data	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet	
1/10/95	0	20.5	0	20.5	0
1/11/95	2	20.1	2	20.4	2
1/11/95	7	20	7	20.2	7
1/12/95	23.25	19.5	23.25	20	23.25
1/12/95	31	19.1	31	20	31
1/13/95	48	18	48	19.2	48
1/17/95	144	13.5	144		144
1/21/95	244	10.2	244		244
1/24/95	317	5.4	317		317

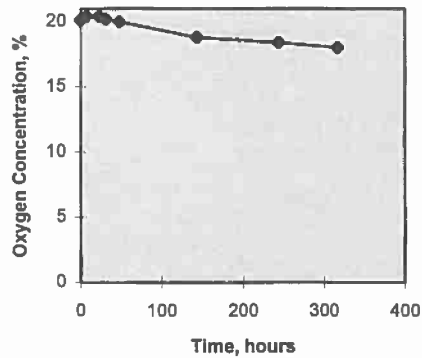


**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

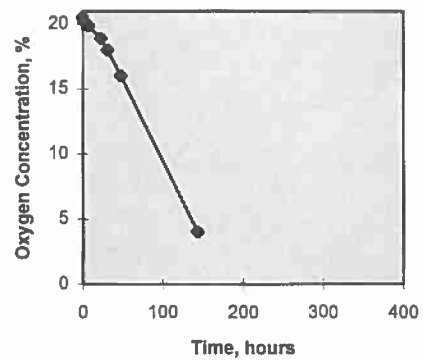
**Oxygen Data**

Date	MP -5				MP -6			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0	20.1	0	20.2	0	20.5	0	20.5
1/11/95	2	20.2	2	20.4	2	20.2	7	19.1
1/11/95	7	20.4	7	20.5	7	19.9	23.25	19
1/12/95	23.25	20.4	23.25	19.9	23.25	18.9	31	
1/12/95	31	20.2	31	20	31	18	48	
1/13/95	48	20	48	19.5	48	16	144	
1/17/95	144	18.8	317	17.2	144	4	244	
1/21/95	244	18.4			244		317	
1/24/95	317	18			317			

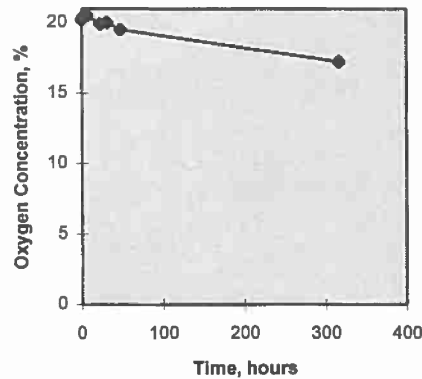
**Oxygen at MP-5 2 ft**



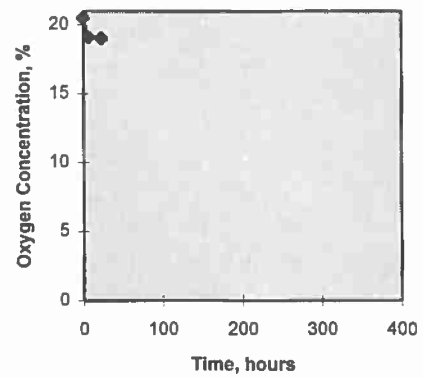
**Oxygen at MP-6 2 ft**



**Oxygen at MP-5 4 ft**



**Oxygen at MP-6 4 ft**

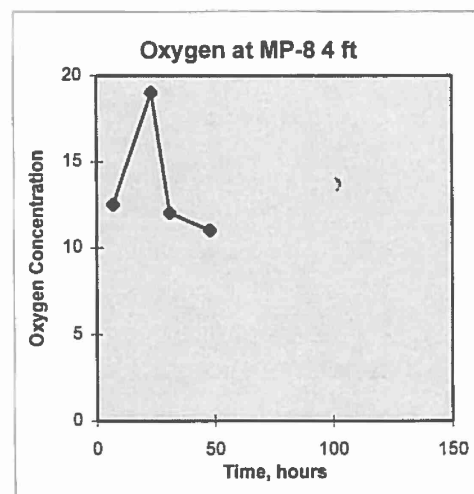
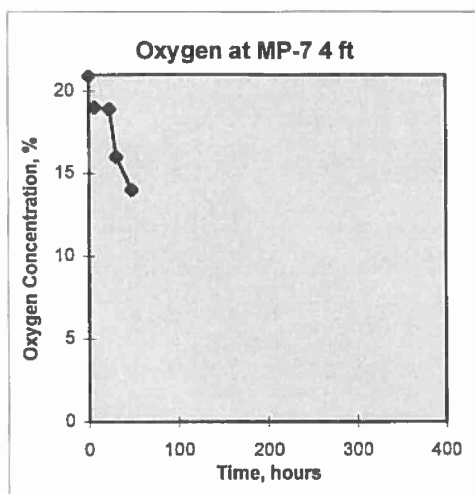
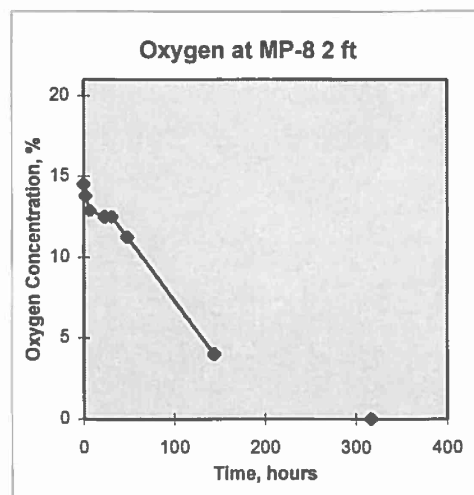
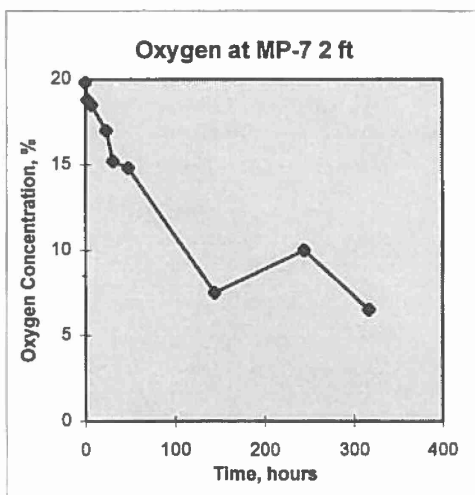


**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

**Oxygen Data**

Date	MP -7			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0	19.8	0	20.9
1/11/95	2	18.8	2	
1/11/95	7	18.5	7	19
1/12/95	23.25	17	23.25	18.9
1/12/95	31	15.2	31	16
1/13/95	48	14.8	48	14
1/17/95	144	7.5	144	
1/21/95	244	10	244	
1/24/95	317	6.5	317	

MP -8			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	14.5	0	
2	13.8	2	
7	12.9	7	12.5
23.25	12.5	23.25	19
31	12.5	31	12
48	11.25	48	11
144	4	144	
244			
317	0	317	

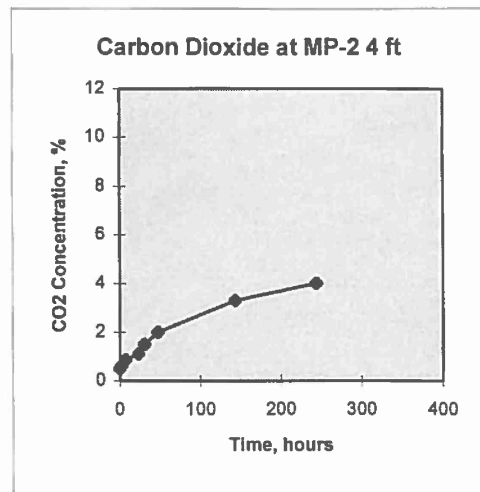
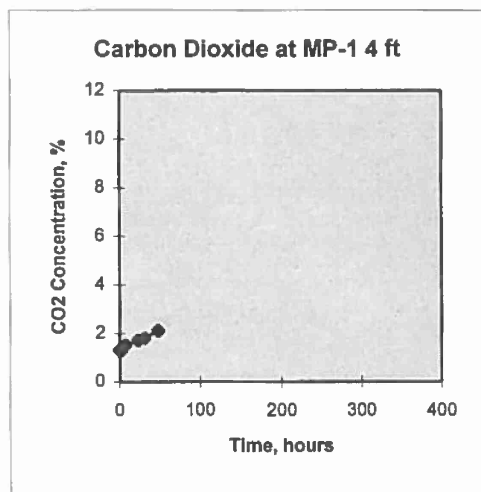
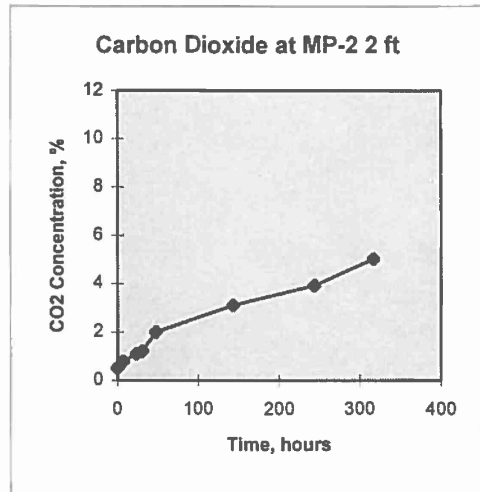
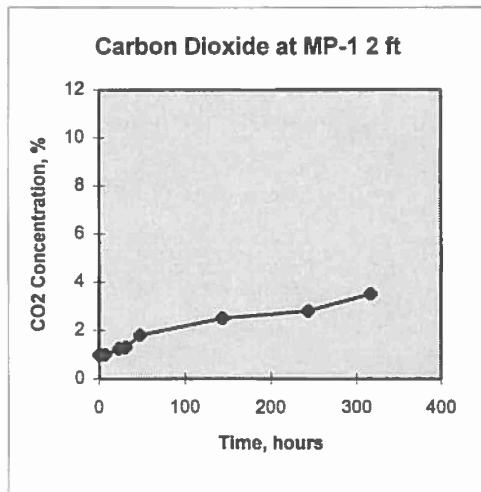


**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

**CO2 Data**

Date	MP -1			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0	1	0	1.3
1/11/95	2	1	2	1.3
1/11/95	7	1	7	1.5
1/12/95	23.25	1.25	23.25	1.7
1/12/95	31	1.3	31	1.8
1/13/95	48	1.8	48	2.1
1/17/95	144	2.5	144	
1/21/95	244	2.8	244	
1/24/95	317	3.5	317	

MP -2			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	0.5	0	0.5
2	0.6	2	0.6
7	0.8	7	0.85
23.25	1.1	23.25	1.1
31	1.2	31	1.5
48	2	48	2
144	3.1	144	3.3
244	3.9	244	4
317	5	317	

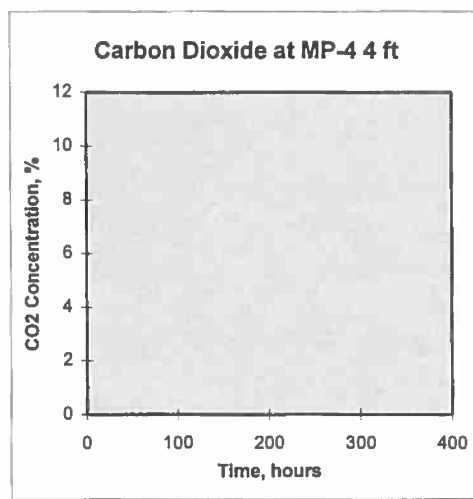
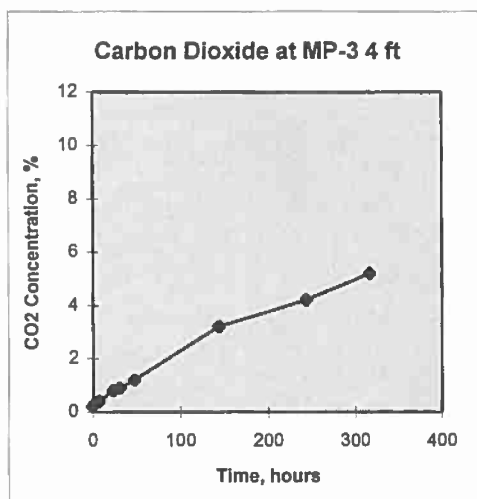
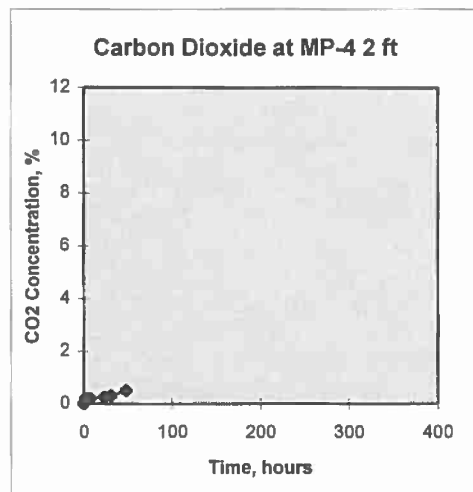
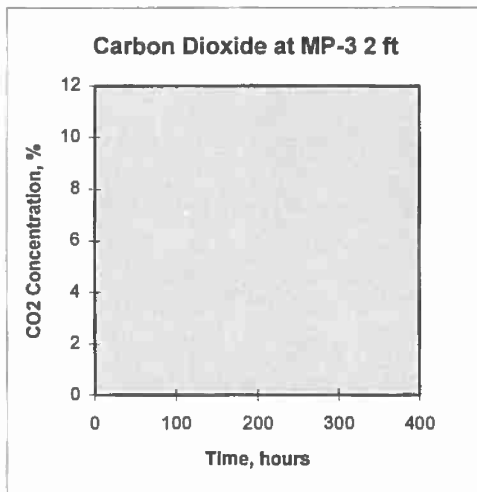




**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

**CO2 Data**

CO2 Data		MP -3			MP -4			
Date	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0		0	0.2	0	0	0	
1/11/95	2		2	0.3	2	0.2	2	
1/11/95	7		7	0.4	7	0.2	7	
1/12/95	23.25		23.25	0.8	23.25	0.25	23.25	
1/12/95	31		31	0.9	31	0.3	31	
1/13/95	48		48	1.2	48	0.5	48	
1/17/95	144		144	3.2	144		144	
1/21/95	244		244	4.2	244		244	
1/24/95	317		317	5.2	317		317	

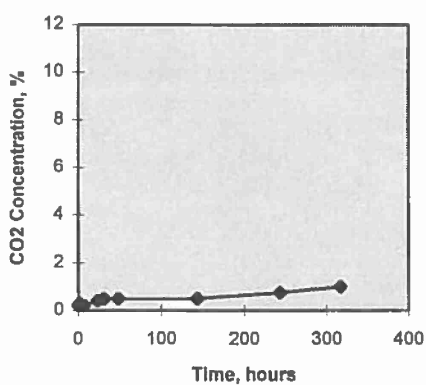


**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

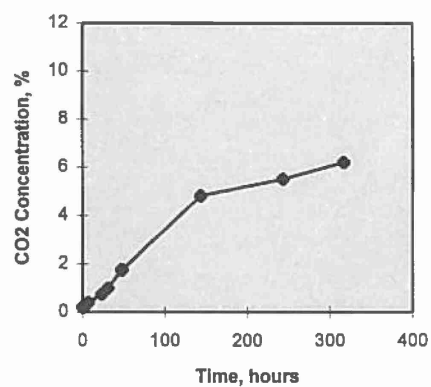
**CO2 Data**

Date	MP -5				MP -6			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0	0.2	0	0.1	0	0.2	0	0.2
1/11/95	2	0.3	2	0.2	2	0.2	2	
1/11/95	7	0.2	7	0.2	7	0.4	7	1.5
1/12/95	23.25	0.4	23.25	0.8	23.25	0.75	23.25	1.2
1/12/95	31	0.5	31	1	31	1	31	
1/13/95	48	0.5	48	0.8	48	1.75	48	
1/17/95	144	0.5	144		144	4.8	144	
1/21/95	244	0.75	244		244	5.5	244	
1/24/95	317	1	317	1	317	6.2	317	

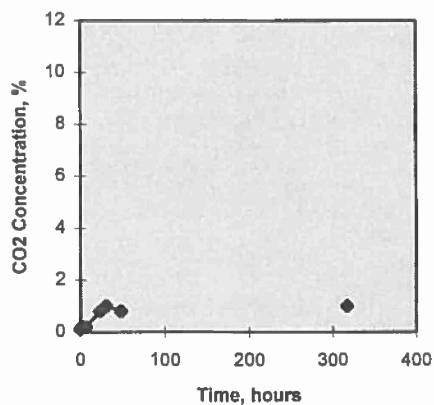
**Carbon Dioxide at MP-5 2 ft**



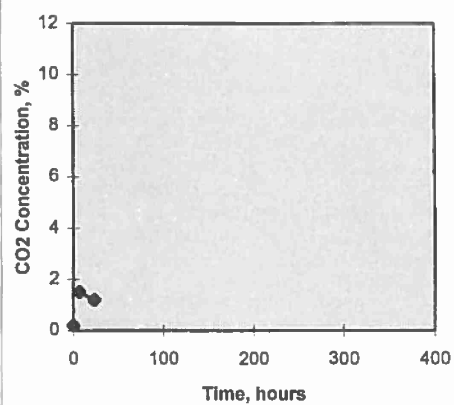
**Carbon Dioxide at MP-6 2 ft**



**Carbon Dioxide at MP-5 4 ft**



**Carbon Dioxide at MP-6 4 ft**

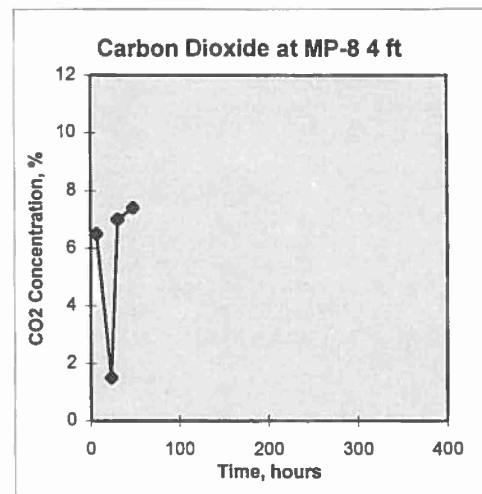
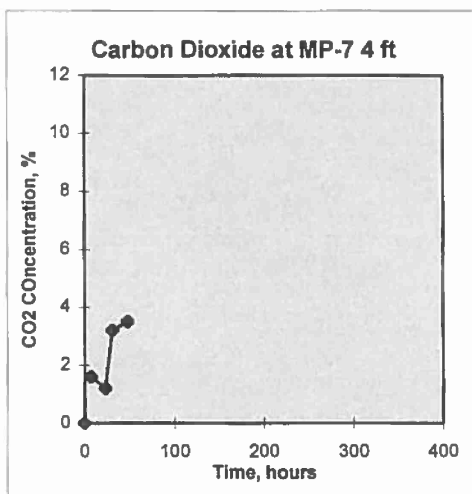
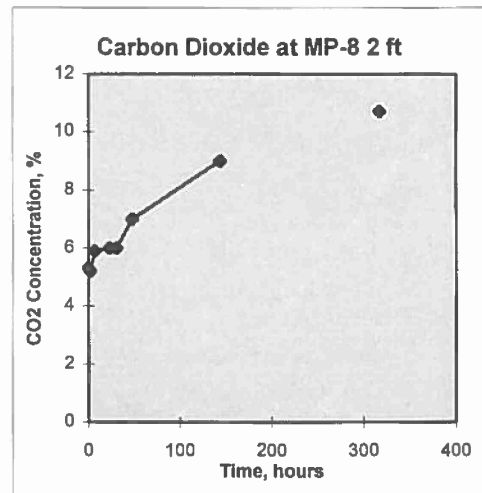
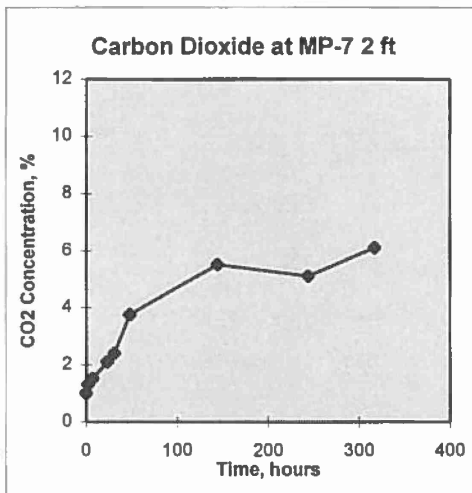


**In Situ Respiration Data for Tyndall Air Force Base  
Test #2  
January 9 through 23, 1995**

**CO2 Data**

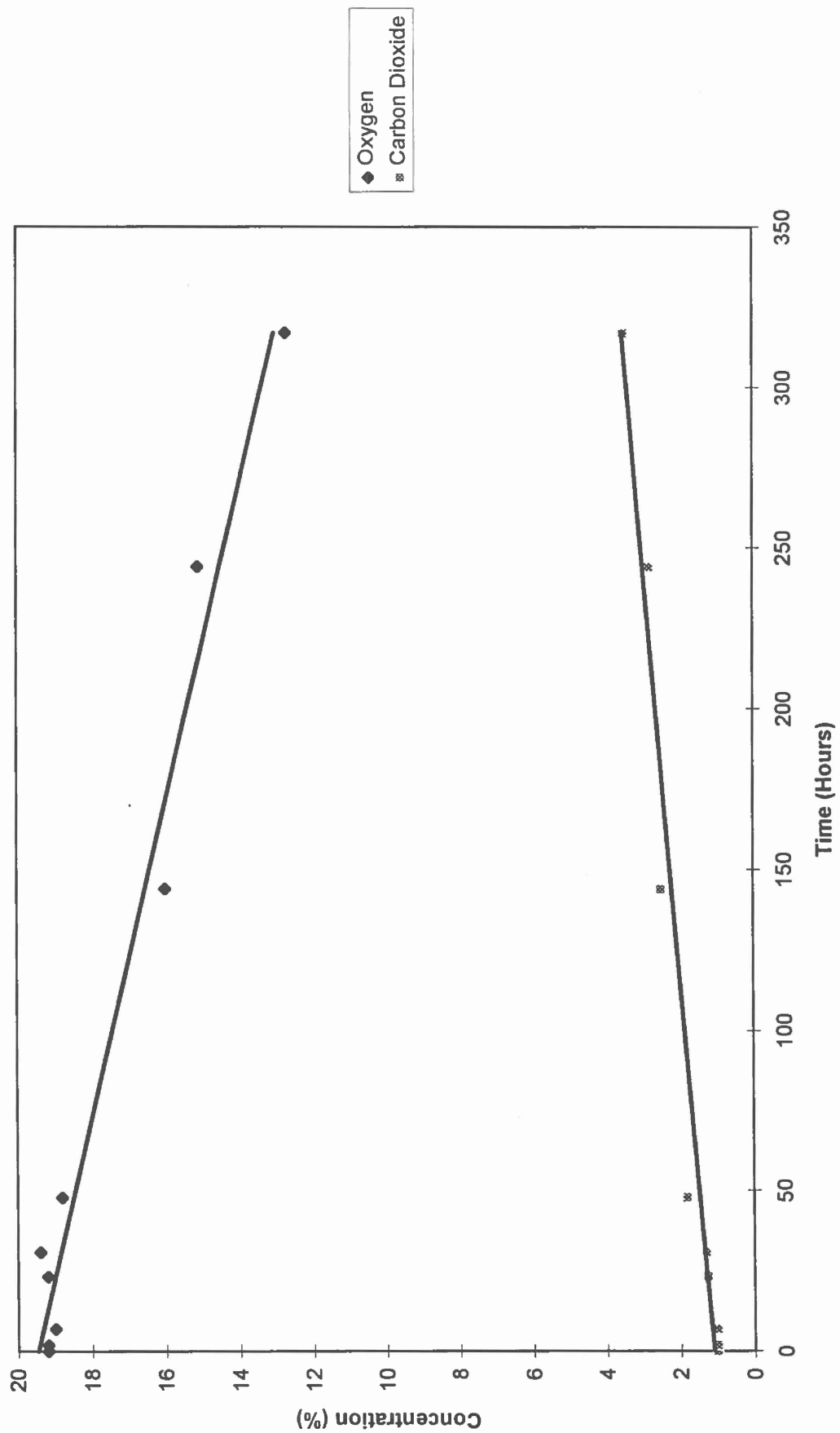
Date	MP -7			
	Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
1/10/95	0	1	0	0
1/11/95	2	1.3	2	
1/11/95	7	1.5	7	1.6
1/12/95	23.25	2.1	23.25	1.2
1/12/95	31	2.4	31	3.2
1/13/95	48	3.75	48	3.5
1/17/95	144	5.5	144	
1/21/95	244	5.1	244	
1/24/95	317	6.1	317	

MP -8			
Elapsed Time	Depth 2 feet	Elapsed Time	Depth 4 feet
0	5.3	0	
2	5.2	2	
7	5.9	7	6.5
23.25	6	23.25	1.5
31	6	31	7
48	7	48	7.4
144	9	144	
244		244	
317	10.7	317	

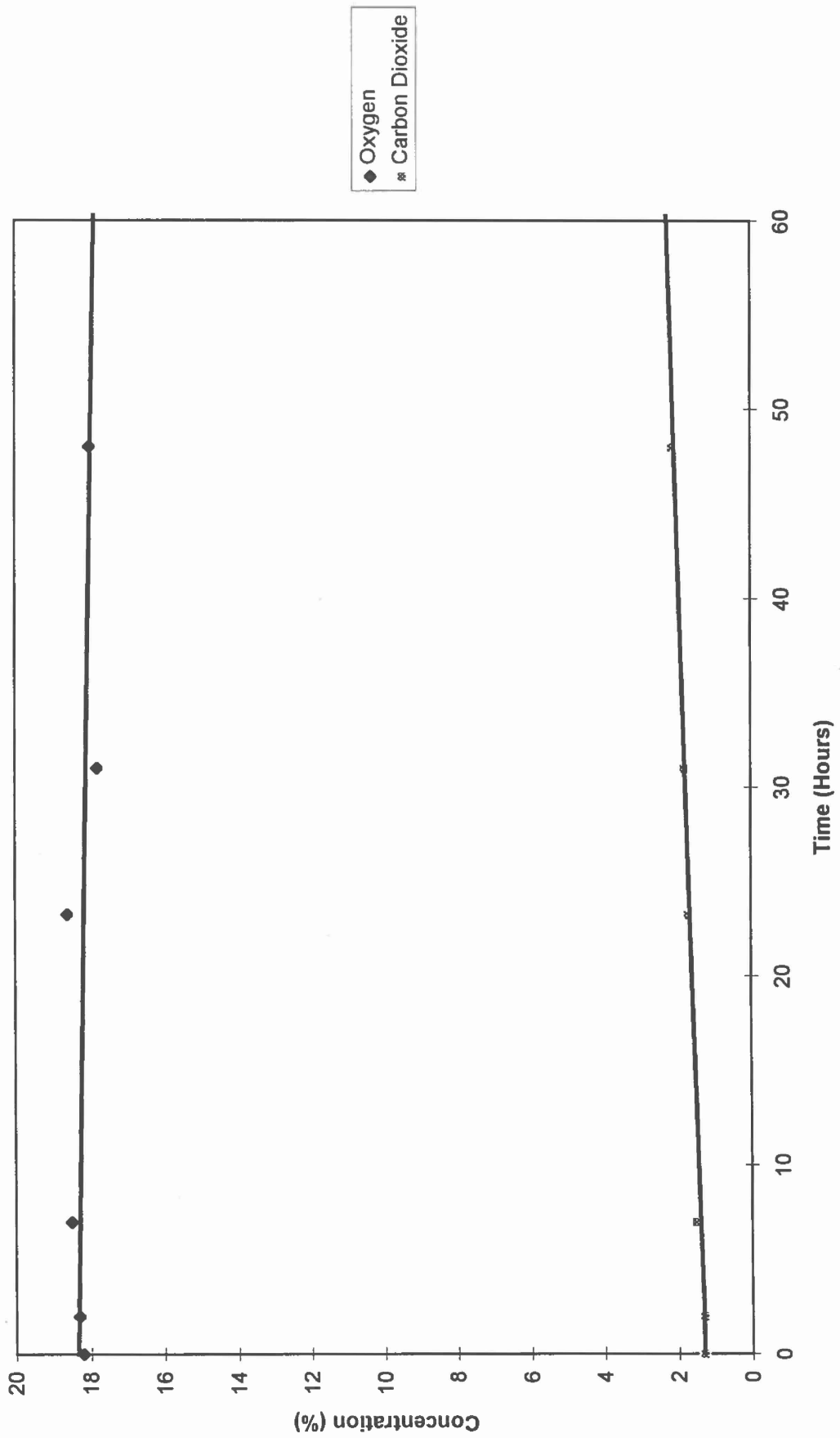




Oxygen and Carbon Dioxide at MP-1 at 2 Feet  
January 9 through 23, 1995

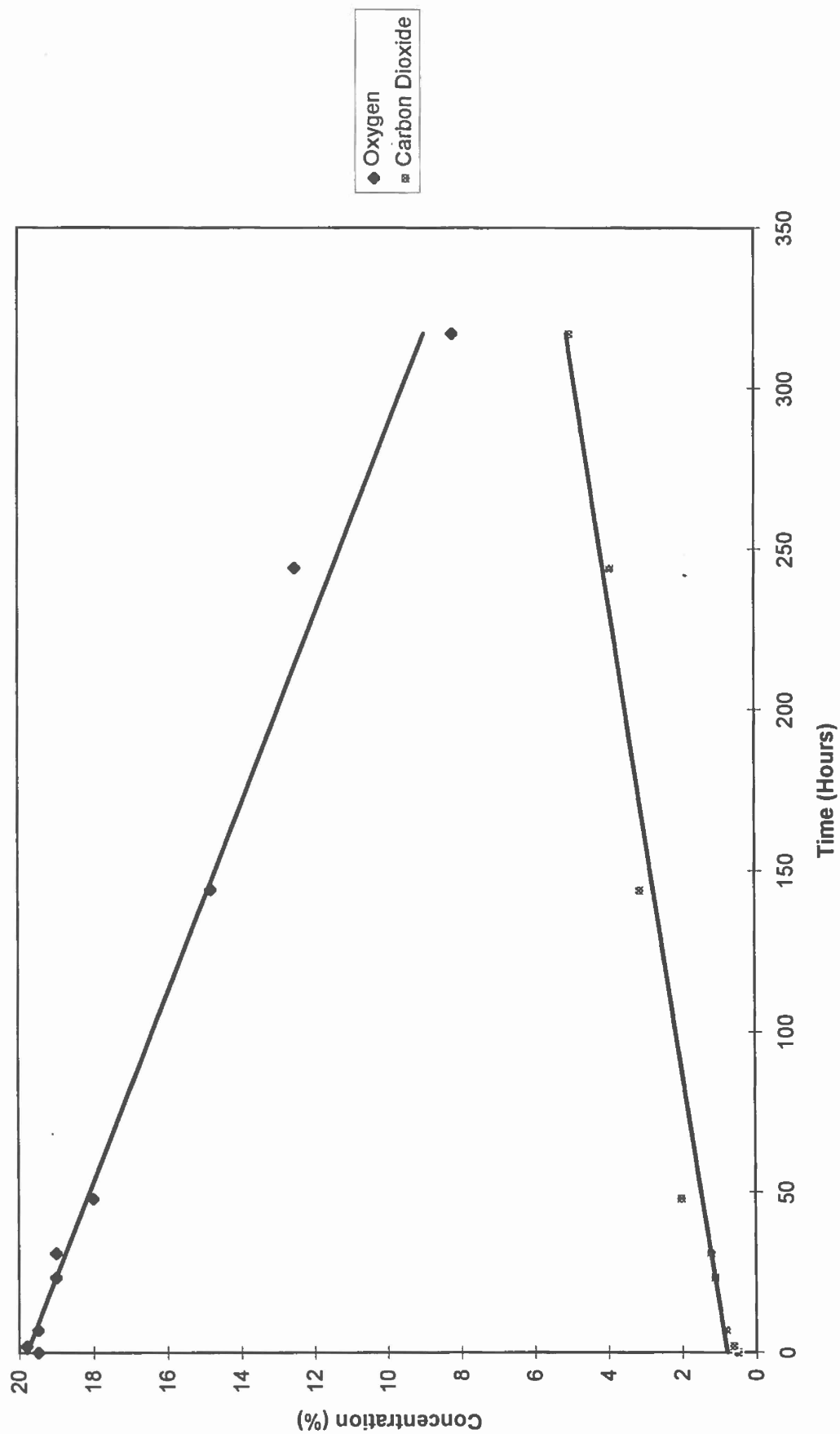


Oxygen and Carbon Dioxide at MP-1 at 4 Feet  
January 9 through 23, 1995



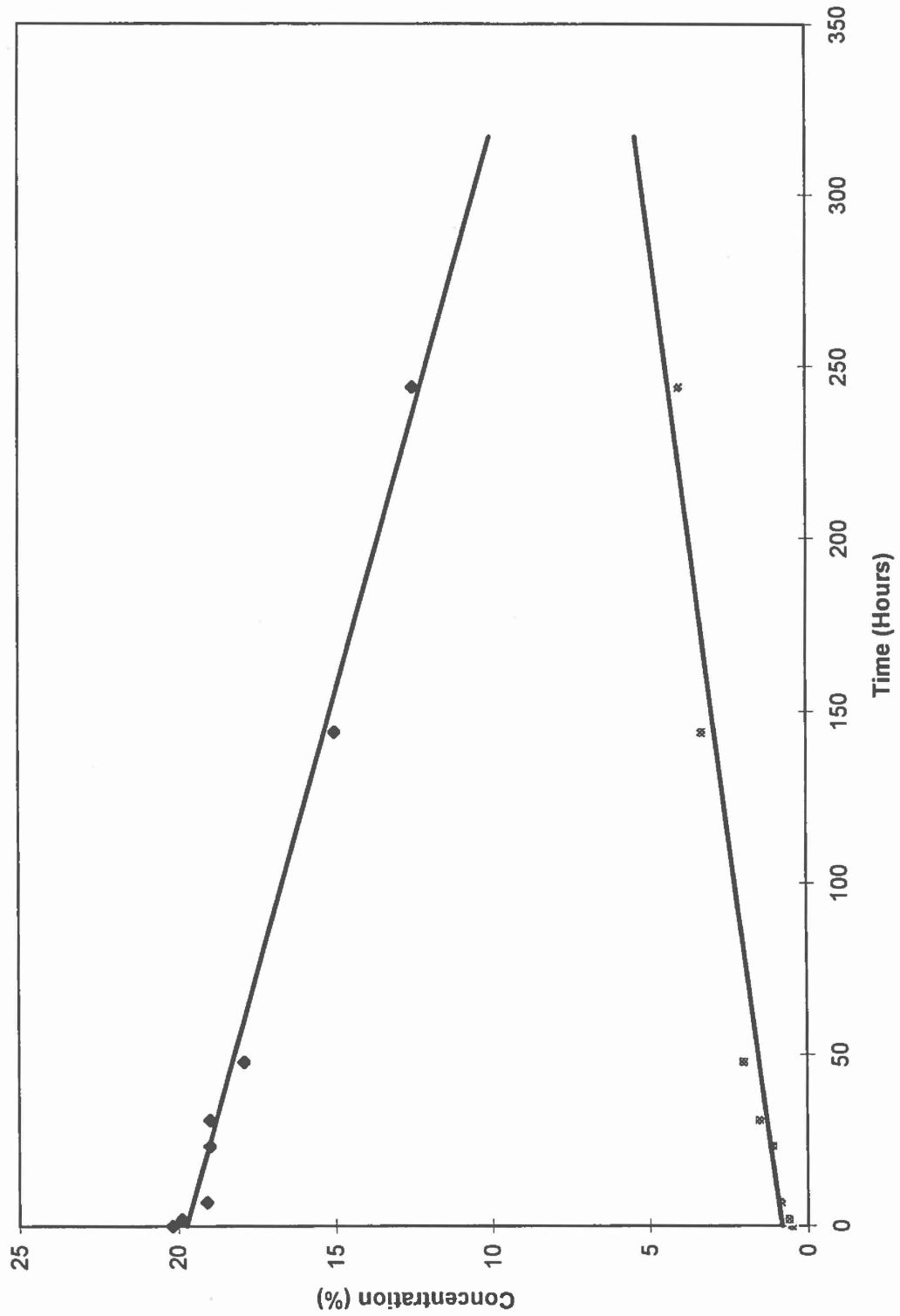
SUMMARY OUTPUT		Respiration Test #2							
		MP-2 @ 2 foot							
Regression Statistics									
Multiple R	0.992863935								
R Square	0.985778794								
Adjusted R Square	0.983747193								
Standard Error	0.516005442								
Observations	9								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	129.1961687	129.19617	485.223	1.00375E-07				
Residual	7	1.863831311	0.2662616						
Total	8	131.06							
		Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.000%	Upper 95.000%	
Intercept	19.79989609	0.222235544	89.094191	5.9E-12	19.27439291	20.325399	19.27439291	20.32539927	
X Variable 1	-0.034179559	0.001551658	-22.02777	1E-07	-0.037848644	-0.0305105	-0.037848644	-0.030510474	
SUMMARY OUTPUT		Respiration Test #2							
		MP-2 @ 4 foot							
Regression Statistics									
Multiple R	0.494467384								
R Square	0.244497994								
Adjusted R Square	0.055622492								
Standard Error	0.292615038								
Observations	6								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	0.11083909	0.1108391	1.29449	0.318747066				
Residual	4	0.342494243	0.0856236						
Total	5	0.453333333							
		Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.000%	Upper 95.000%	
Intercept	18.37900195	0.175107421	104.95844	4.9E-08	17.89282481	18.865179	17.89282481	18.8651791	
X Variable 1	-0.007856285	0.006905059	-1.137758	0.31875	-0.027027843	0.0113153	-0.027027843	0.011315272	

Oxygen and Carbon Dioxide at MP-2 at 2 Feet  
January 9 through 23, 1995



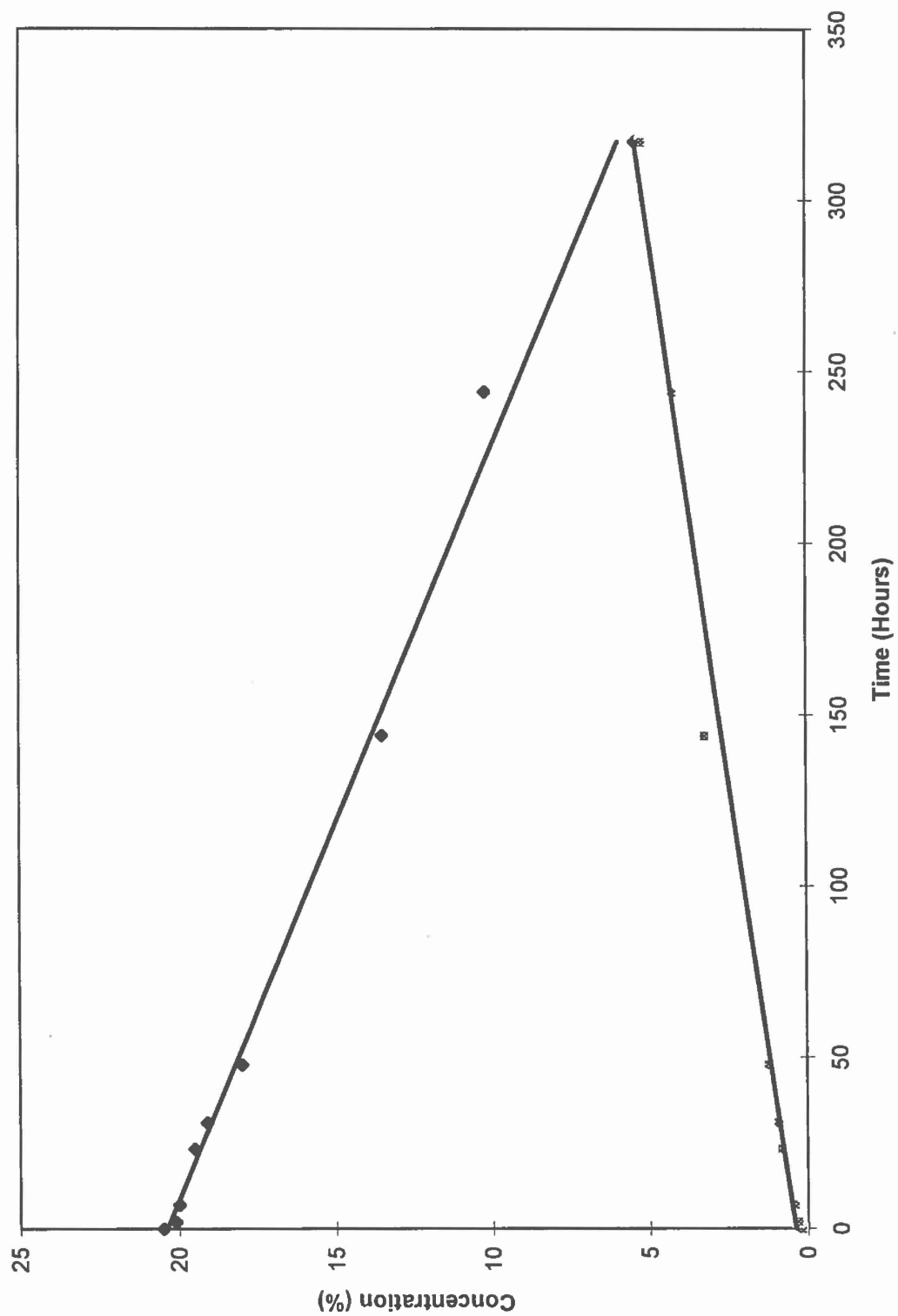


Oxygen and Carbon Dioxide at MP-2 at 4 Feet  
January 9 through 23, 1995



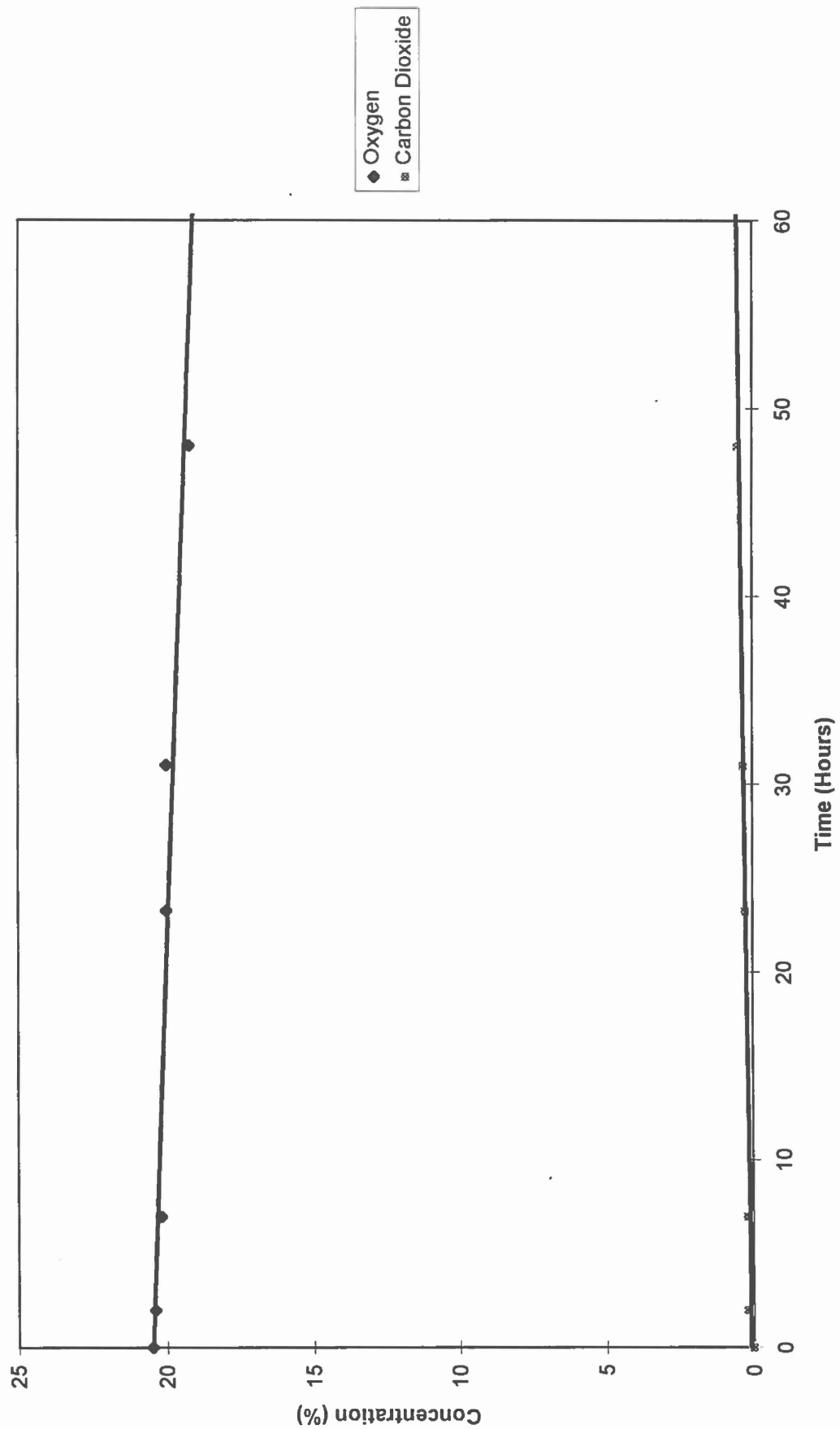


Oxygen and Carbon Dioxide at MP-3 at 4 Feet  
January 9 through 23, 1995



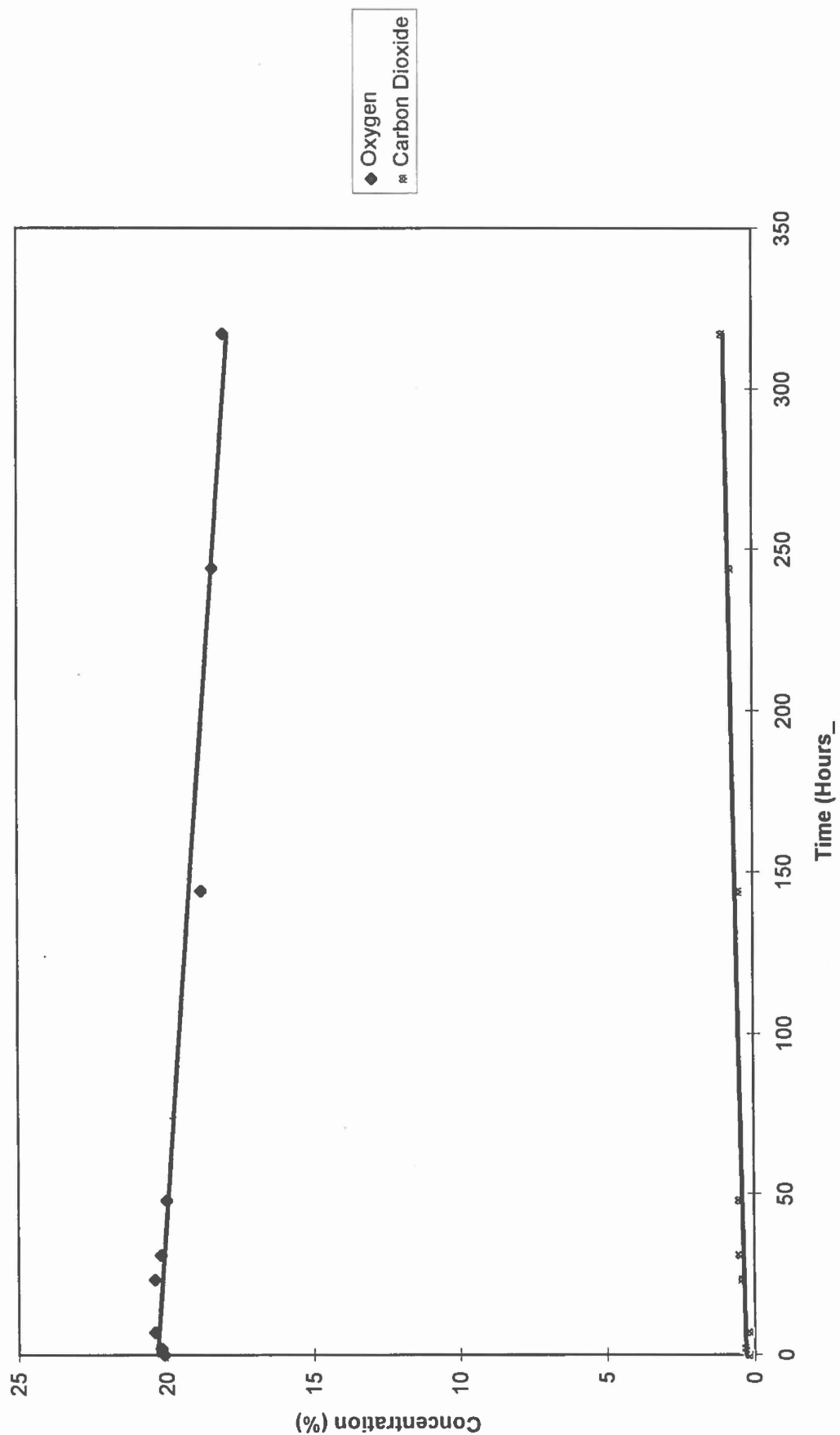


Oxygen and Carbon Dioxide at MP-4 at 2 Feet  
January 9 through 23, 1995

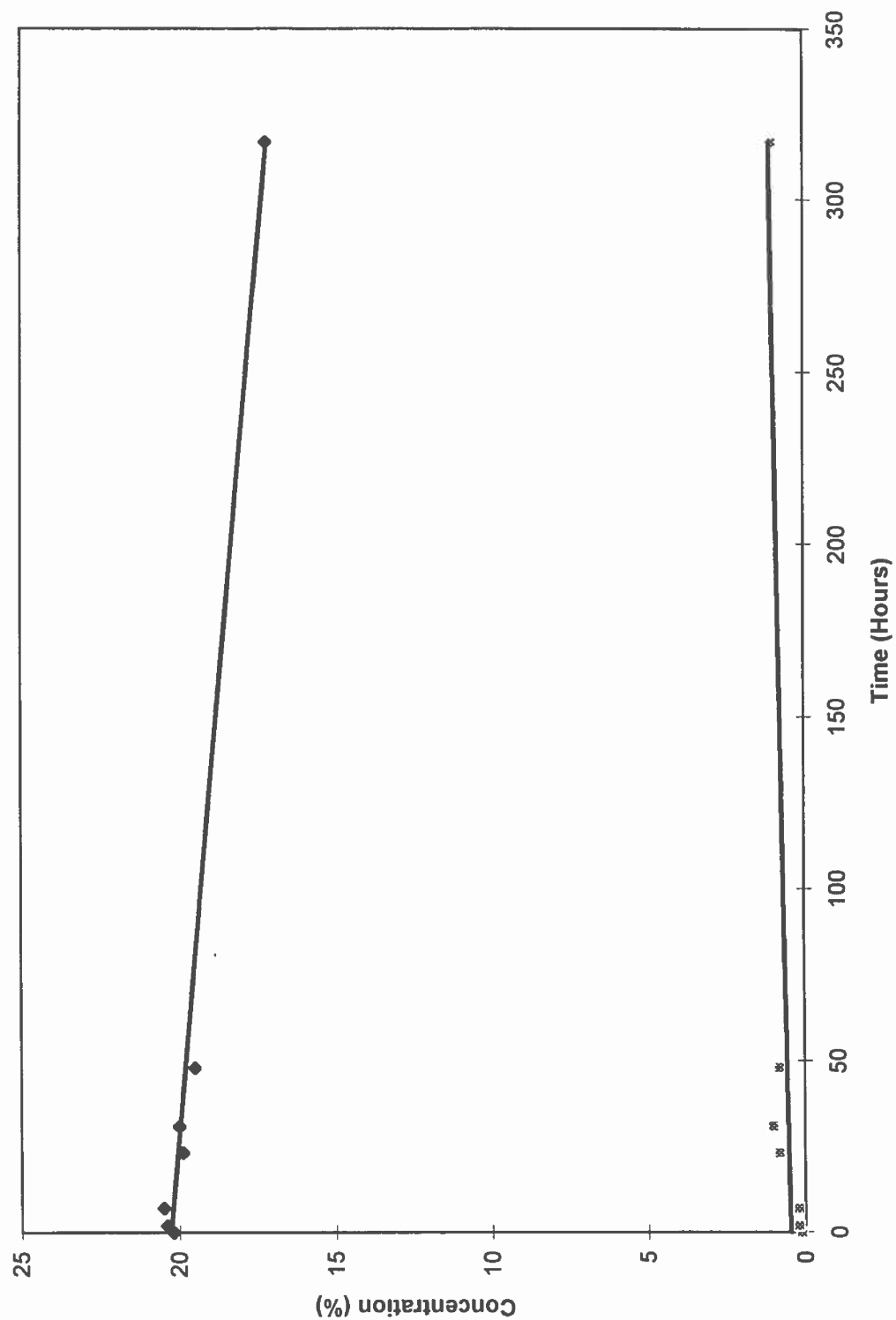




Oxygen and Carbon Dioxide at MP-5 at 2 Feet  
January 9 through 23, 1995



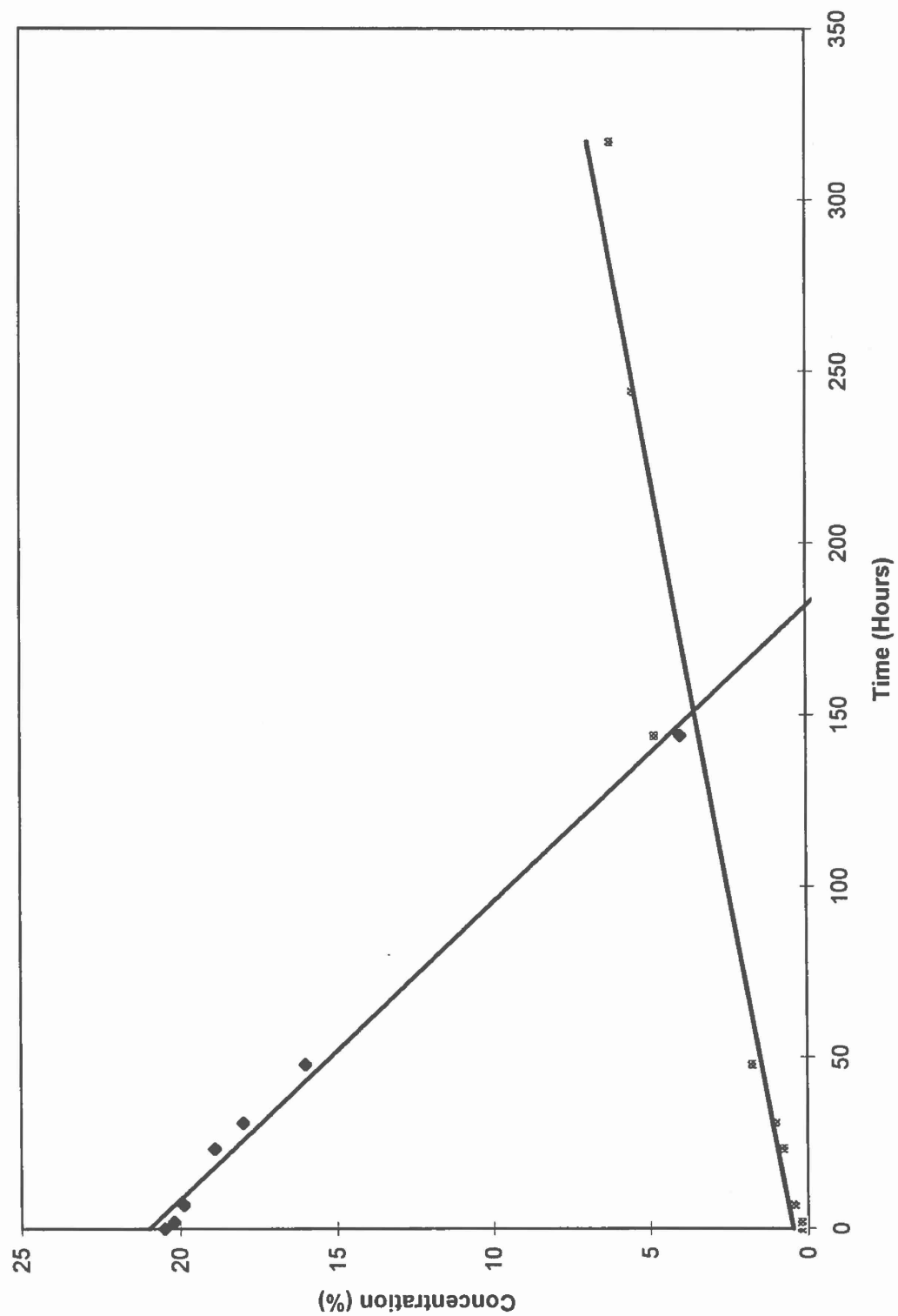
Oxygen and Carbon Dioxide at MP-5 at 4 Feet  
January 9 through 23, 1995





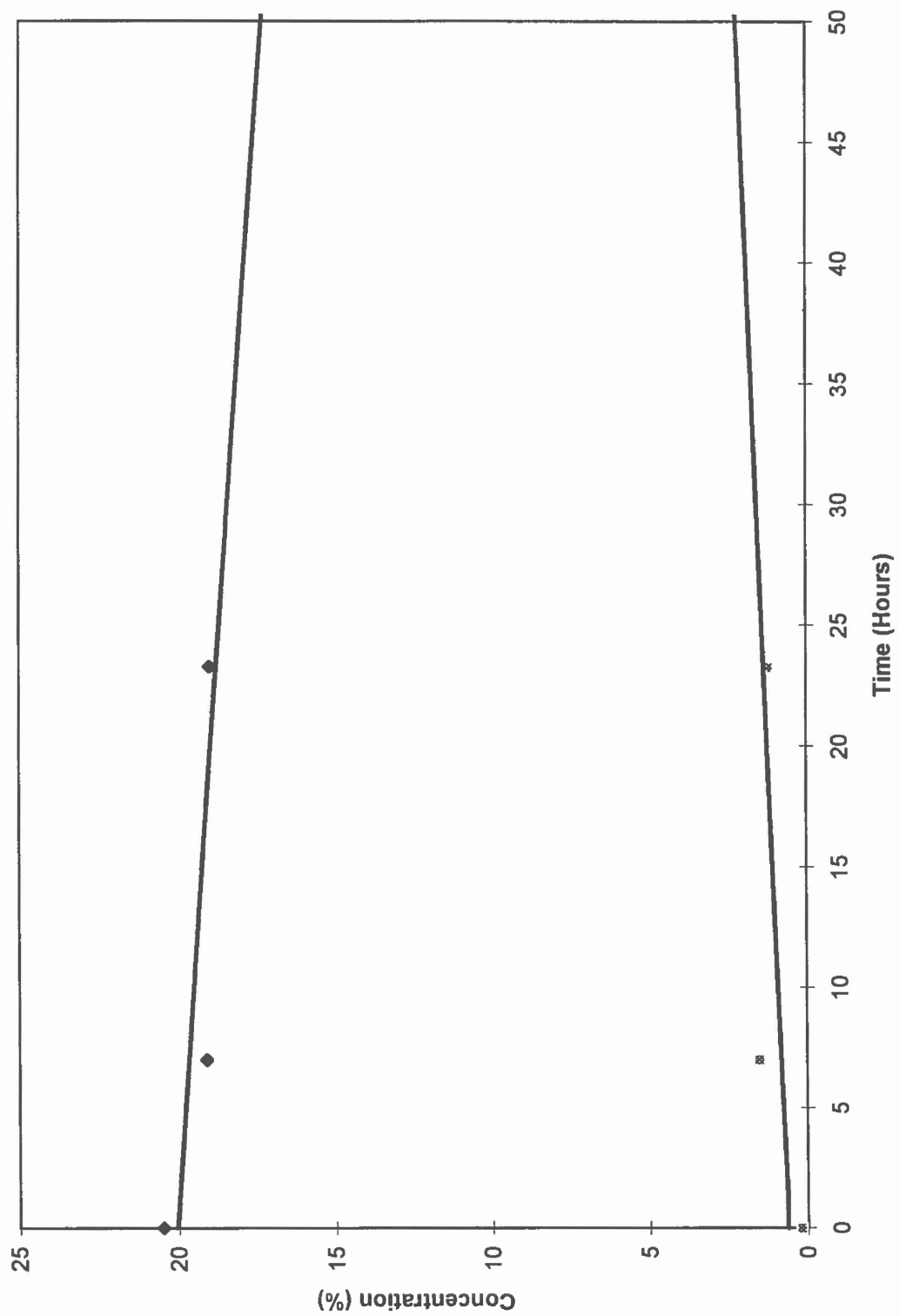


Oxygen and Carbon Dioxide at MP-6 at 2 Feet  
January 9 through 23, 1995



◆ Oxygen  
■ Carbon Dioxide

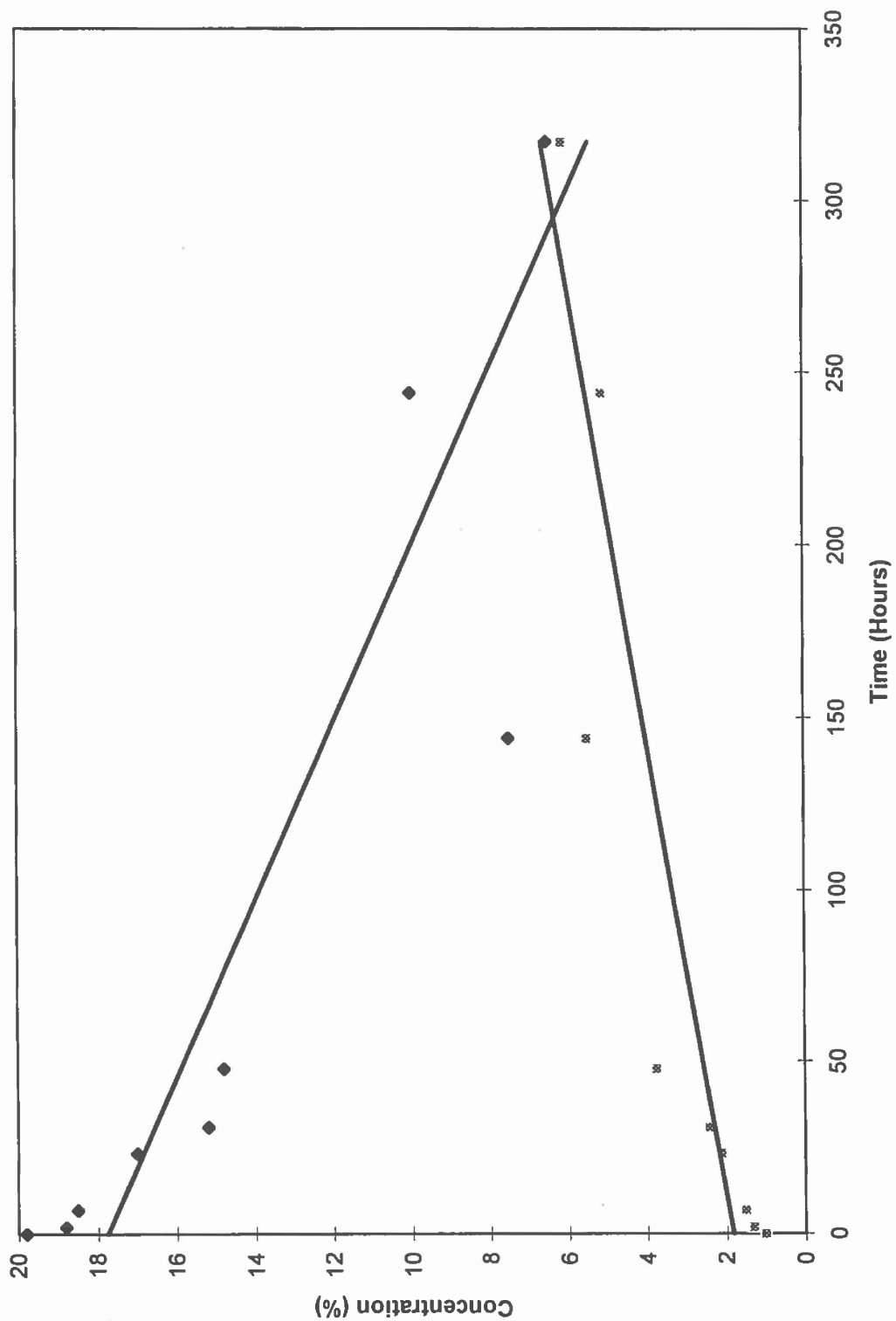
Oxygen and Carbon Dioxide at MP-6 at 4 Feet  
January 9 through 23, 1995



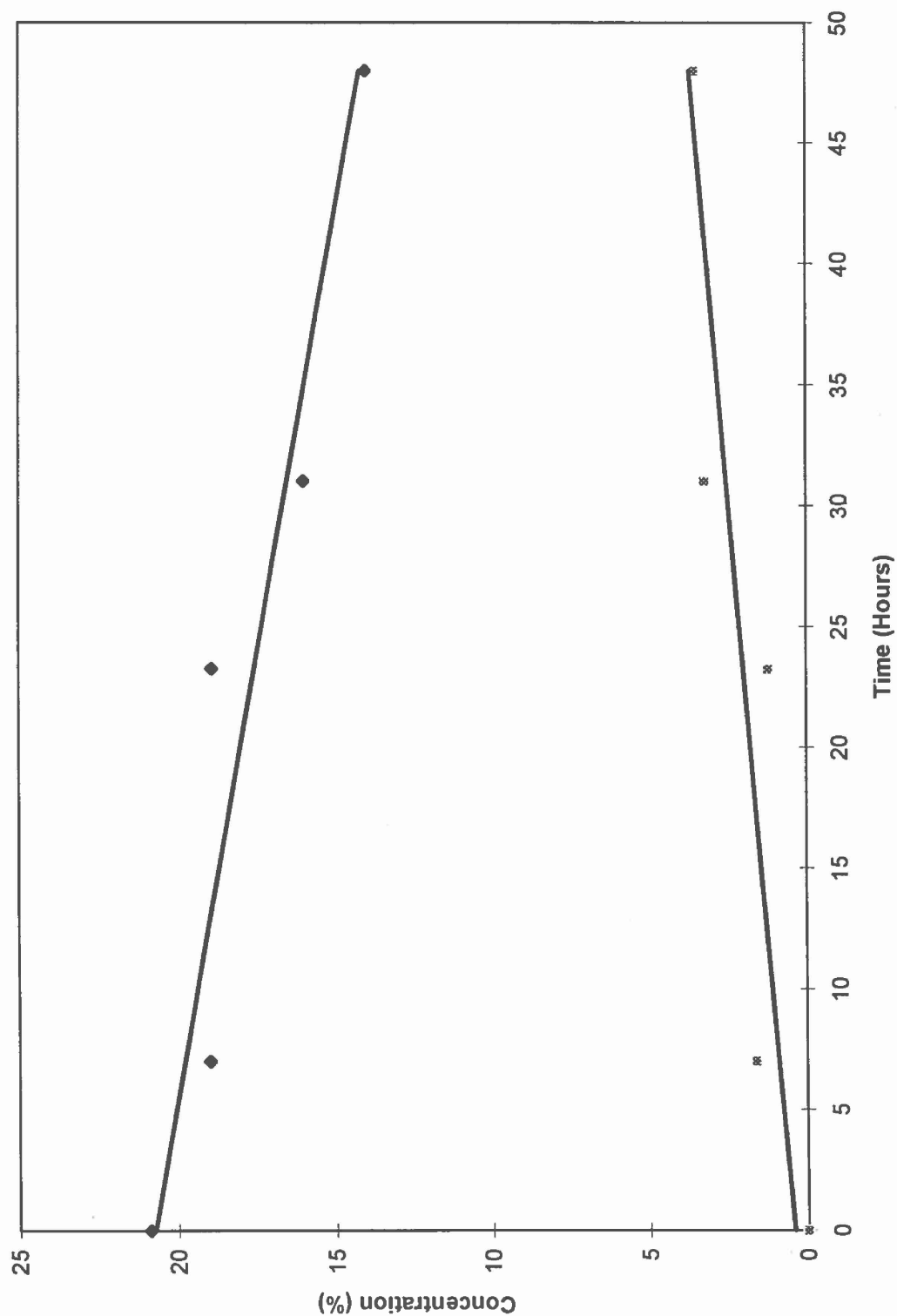
◆ Oxygen  
\* Carbon Dioxide



Oxygen and Carbon Dioxide at MP-7 at 2 Feet  
January 9 through 23, 1995



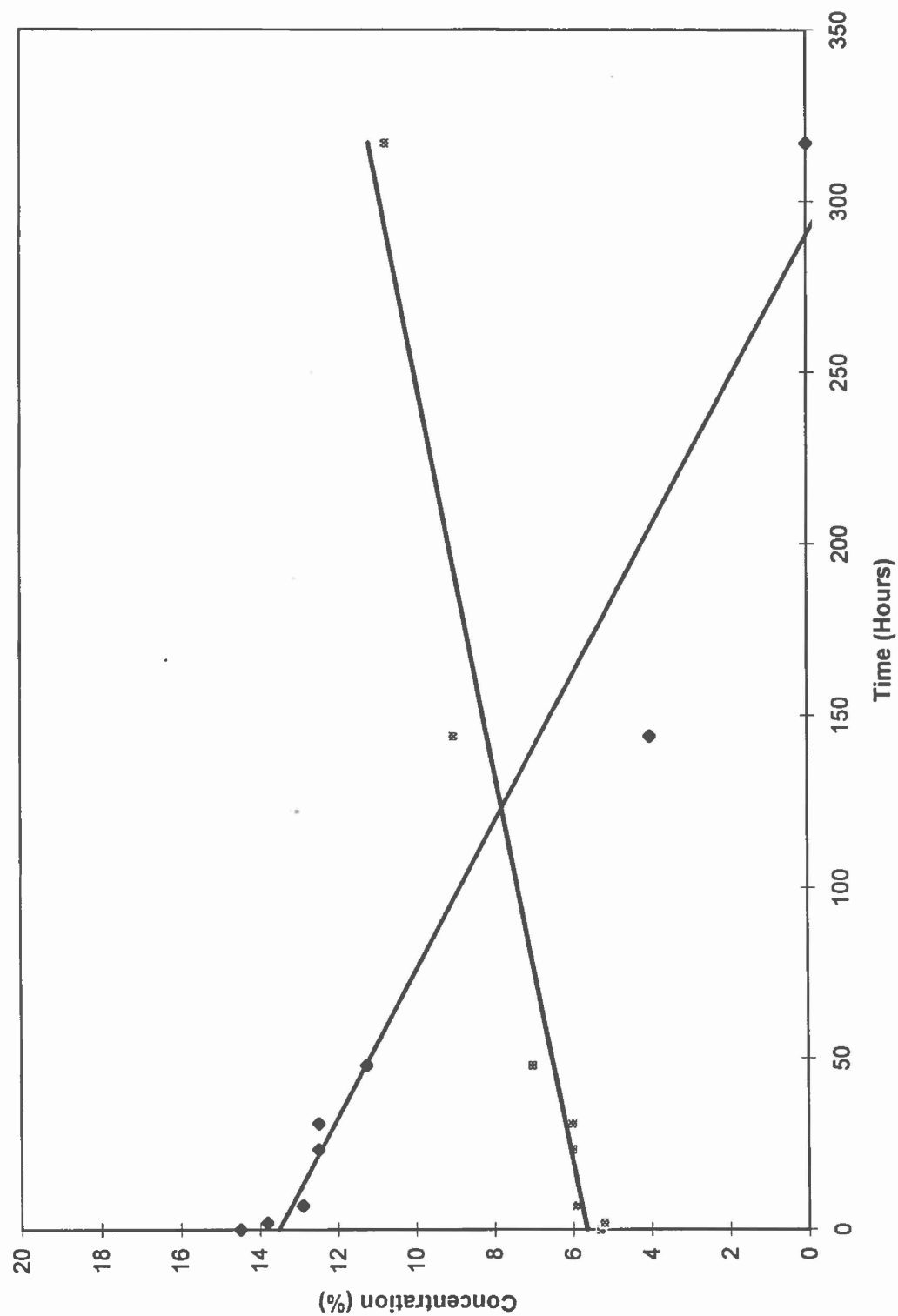
Oxygen and Carbon Dioxide at MP-7 at 4 Feet  
January 9 through 23, 1995



◆ Oxygen  
\* Carbon Dioxide

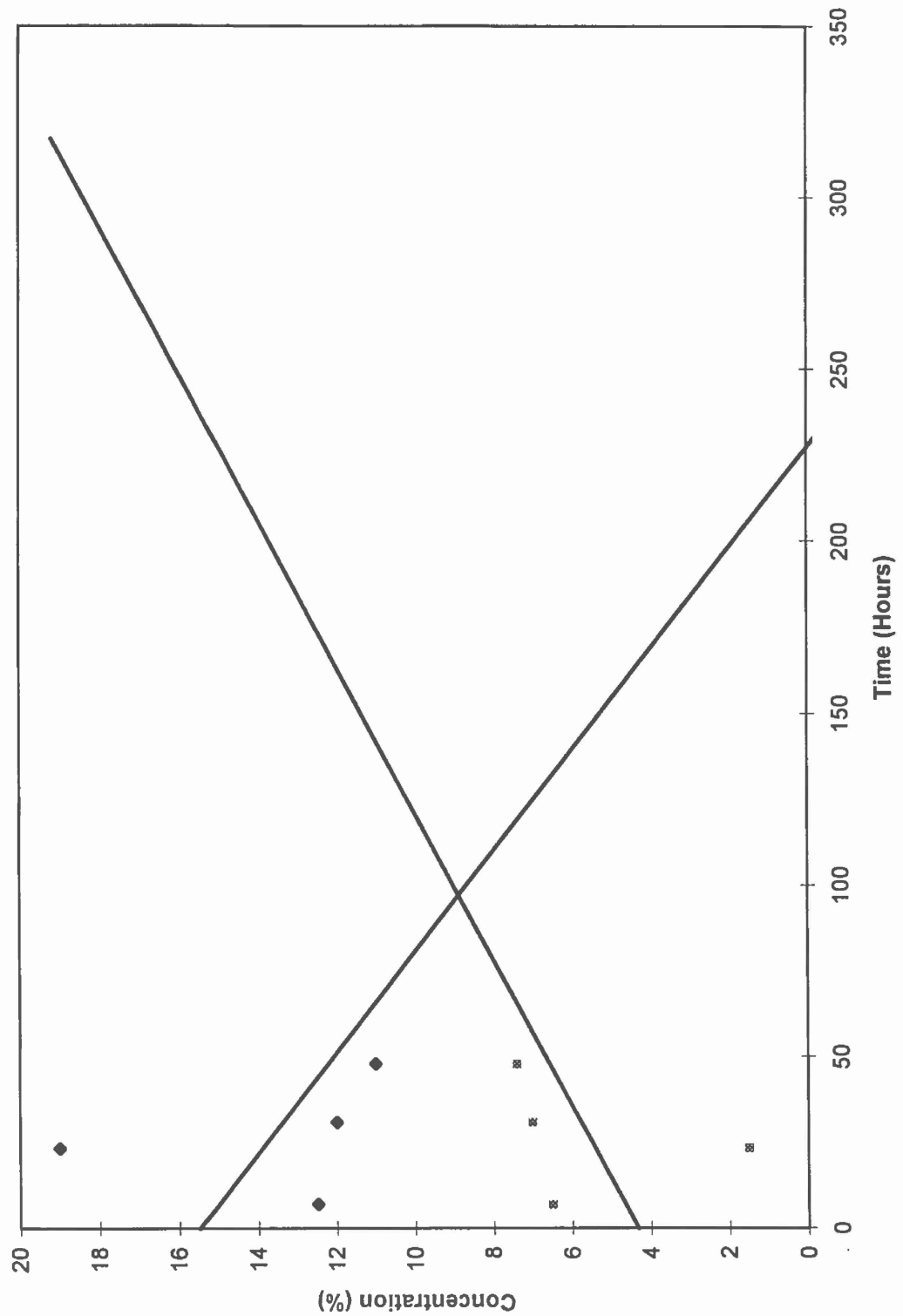
SUMMARY OUTPUT		Respiration Test #2		MP-8 @ 2 foot					
Regression Statistics									
Multiple R	0.97151649								
R Square	0.94384428								
Adjusted R Square	0.93448499								
Standard Error	1.34365302								
Observations	8								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	182.0672668	182.0673	100.8458	5.65453E-05				
Residual	6	10.83242066	1.805403						
Total	7	192.8996875							
		Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.000%	Upper 95.000%
Intercept		13.5084982	0.579182865	23.32337	4.07E-07	12.09128772	14.9257086	12.09128772	14.92570862
X Variable 1		-0.04651461	0.004631915	-10.0422	5.65E-05	-0.057848505	-0.03518071	-0.057848505	-0.035180714
SUMMARY OUTPUT		Respiration Test #2		MP-8 @ 4 foot					
Regression Statistics									
Multiple R	0.31890639								
R Square	0.10170129								
Adjusted R Square	-0.34744807								
Standard Error	4.22203921								
Observations	4								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	1	4.036269808	4.03627	0.226431	0.681093609				
Residual	2	35.65123019	17.82562						
Total	3	39.6875							
		Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.000%	Upper 95.000%
Intercept		15.4846204	4.441734083	3.486166	0.073344	-3.626632228	34.5958729	-3.626632228	34.59587294
X Variable 1		-0.06808679	0.143085295	-0.47585	0.681094	-0.683733552	0.54755998	-0.683733552	0.547559979

Oxygen and Carbon Dioxide at MP-8 at 2 Feet  
January 9 through 23, 1995





# Oxygen and Carbon Dioxide at MP-8 at 4 Feet January 9 through 23, 1995



## **APPENDIX C**

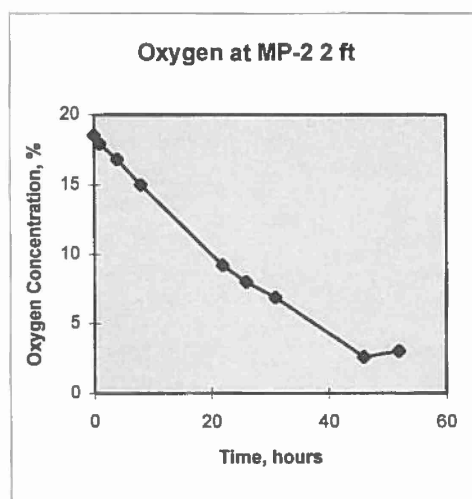
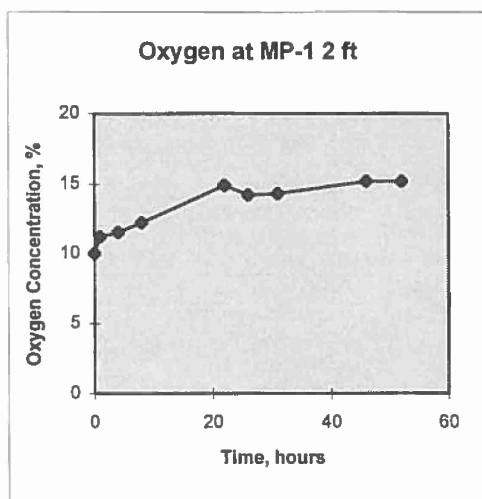
### **OXYGEN AND CARBON DIOXIDE DATA AND REGRESSION ANALYSIS OUTPUT FOR RESPIRATION TEST 3**

**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Oxygen Data**

MP-1		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	10.0
6/21/95	1	11.2
6/21/95	4	11.5
6/21/95	8	12.2
6/22/95	22	14.9
6/22/95	26	14.2
6/22/95	31	14.3
6/23/95	46	15.2
6/23/95	52	15.2

MP-2		
Elapsed Time	Depth 2 feet	
0	18.5	
1	17.9	
4	16.8	
8	15.0	
22	9.2	
26	8.0	
31	6.9	
46	2.6	
52	3.0	

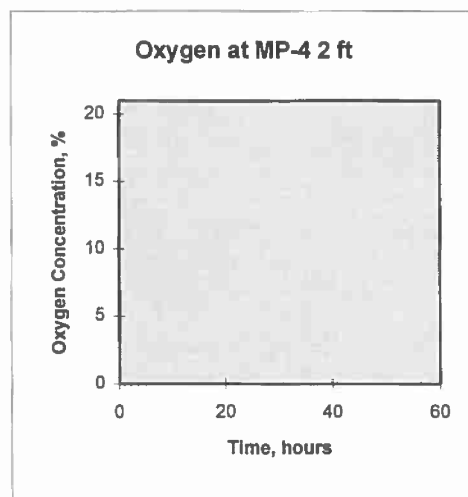
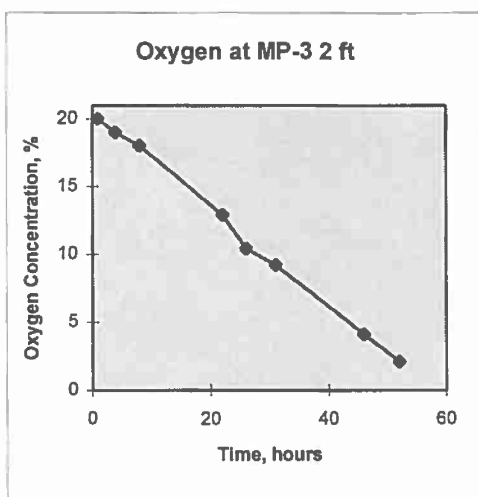


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Oxygen Data**

MP-3		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	20.5
6/21/95	1	20.0
6/21/95	4	19.0
6/21/95	8	18.0
6/22/95	22	12.9
6/22/95	26	10.4
6/22/95	31	9.2
6/23/95	46	4.1
6/23/95	52	2.1

MP-4		
Elapsed Time	Depth 2 feet	
0		
1		
4		
8		
22		
26		
31		
46		
52		

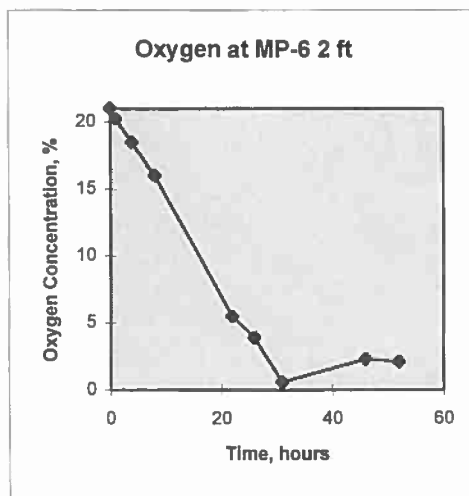
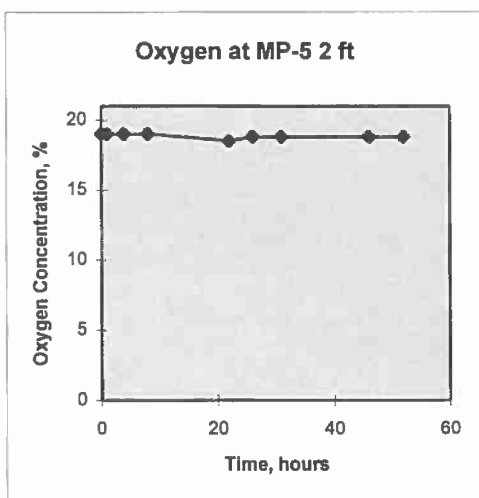


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Oxygen Data**

MP-5		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	19.0
6/21/95	1	19.0
6/21/95	4	19.0
6/21/95	8	19.0
6/22/95	22	18.5
6/22/95	26	18.8
6/22/95	31	18.8
6/23/95	46	18.8
6/23/95	52	18.8

MP-6		
Elapsed Time	Depth 2 feet	
0	21.0	
1	20.2	
4	18.5	
8	16.0	
22	5.5	
26	3.9	
31	0.6	
46	2.3	
52	2.1	

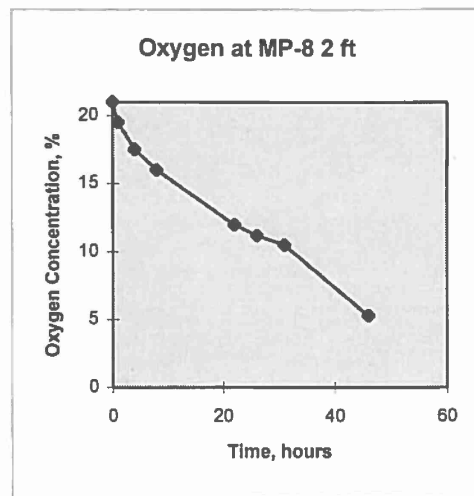
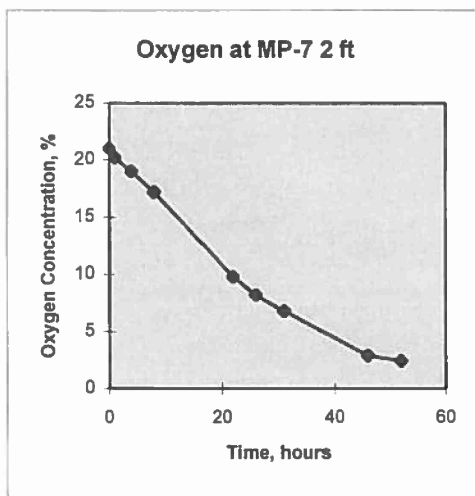


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 19 through 23, 1995**

**Oxygen Data**

MP-7		
Date	Elapsed Time	Depth 2 feet
6/19/95	0	21.0
6/20/95	1	20.2
6/21/95	4	19.0
6/22/95	8	17.2
6/23/95	22	9.8
6/24/95	26	8.2
6/25/95	31	6.8
6/26/95	46	2.9
6/27/95	52	2.4

MP-8		
Elapsed Time	Depth 2 feet	
0	21.0	
1	19.5	
4	17.5	
8	16.0	
22	12.0	
26	11.2	
31	10.5	
46	5.3	
52	5.7	

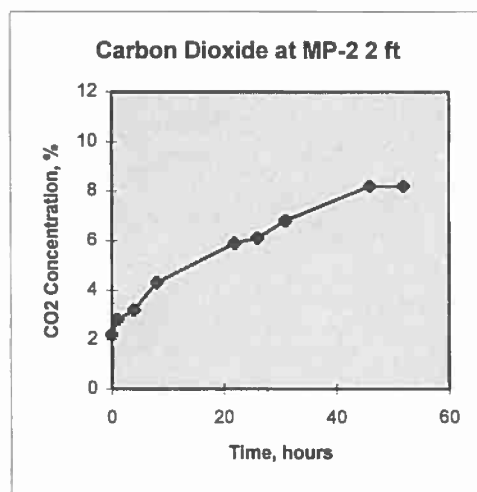
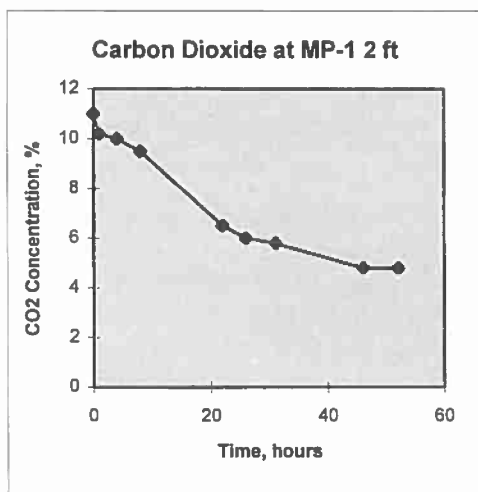


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Carbon Dioxide Data**

MP-1		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	11.0
6/21/95	1	10.2
6/21/95	4	10.0
6/21/95	8	9.5
6/22/95	22	6.5
6/22/95	26	6.0
6/22/95	31	5.8
6/23/95	46	4.8
6/23/95	52	4.8

MP-2		
Elapsed Time	Depth 2 feet	
0	2.2	
1	2.8	
4	3.2	
8	4.3	
22	5.9	
26	6.1	
31	6.8	
46	8.2	
52	8.2	

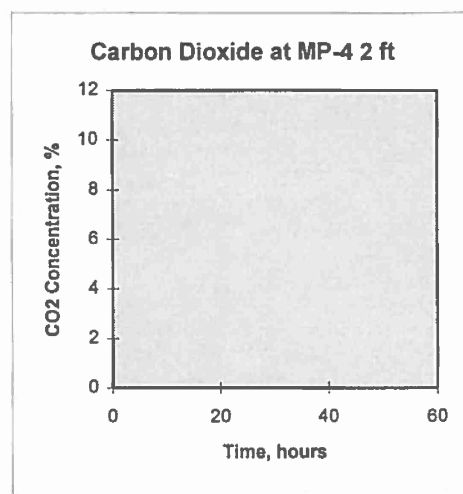
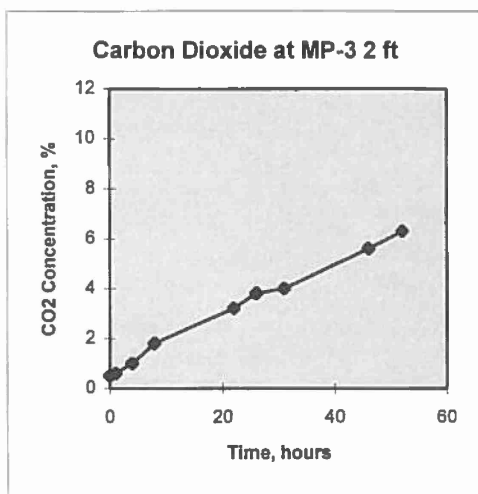


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Carbon Dioxide Data**

MP-3		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	0.5
6/21/95	1	0.6
6/21/95	4	1.0
6/21/95	8	1.8
6/22/95	22	3.2
6/22/95	26	3.8
6/22/95	31	4.0
6/23/95	46	5.6
6/23/95	52	6.3

MP-4	
Elapsed Time	Depth 2 feet
0	
1	
4	
8	
22	
26	
31	
46	
52	



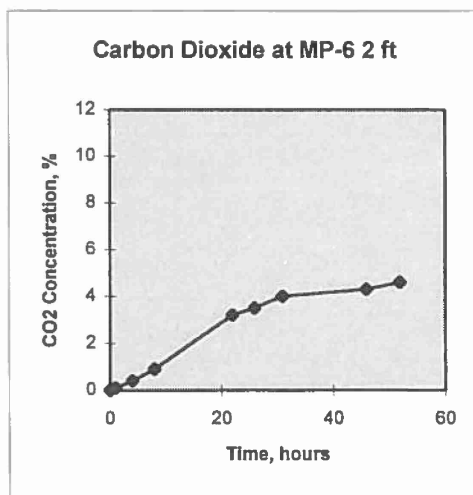
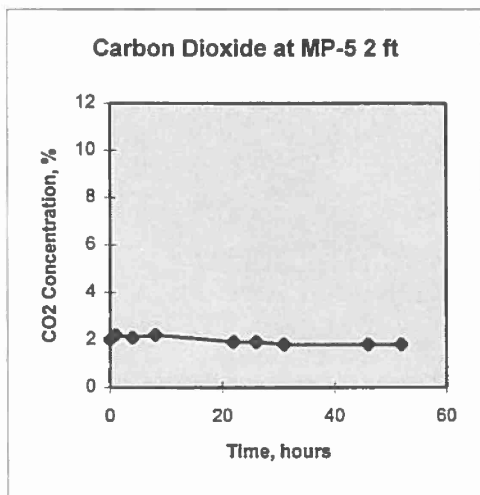


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Carbon Dioxide Data**

MP-5		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	2.0
6/21/95	1	2.2
6/21/95	4	2.1
6/21/95	8	2.2
6/22/95	22	1.9
6/22/95	26	1.9
6/22/95	31	1.8
6/23/95	46	1.8
6/23/95	52	1.8

MP-6		
Elapsed Time	Depth 2 feet	
0	0.0	
1	0.1	
4	0.4	
8	0.9	
22	3.2	
26	3.5	
31	4.0	
46	4.3	
52	4.6	

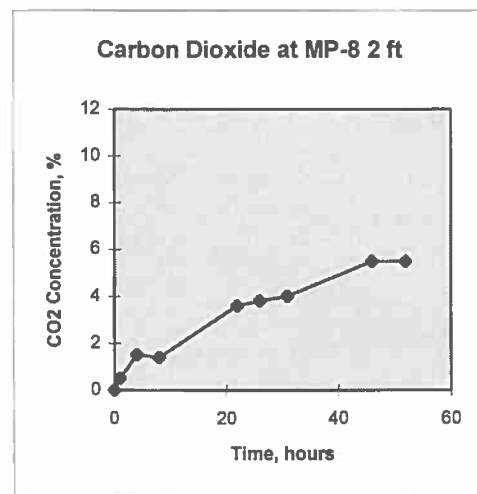
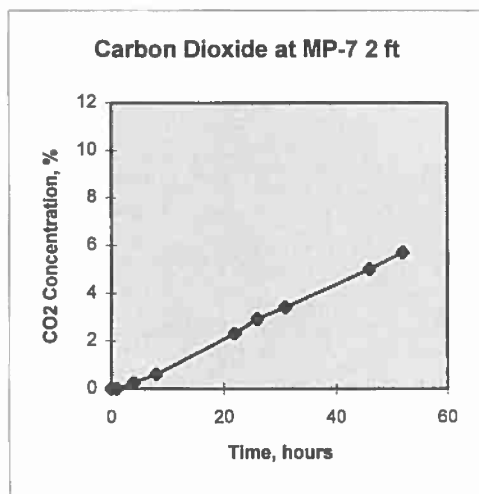


**In Situ Respiration Data for Tyndall Air Force Base  
Test #3  
June 21 through 23, 1995**

**Carbon Dioxide Data**

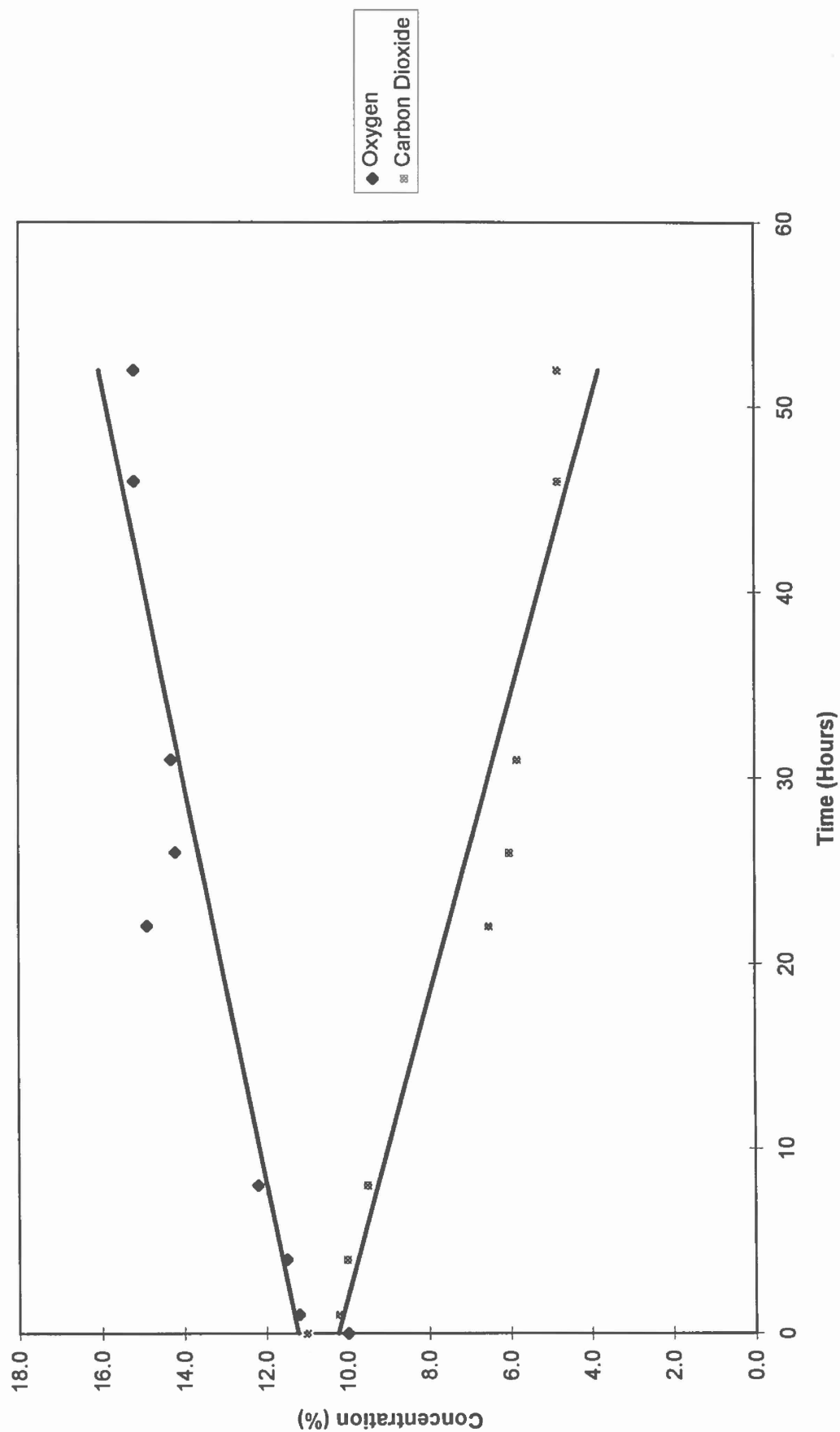
MP-7		
Date	Elapsed Time	Depth 2 feet
6/21/95	0	0.0
6/21/95	1	0.0
6/21/95	4	0.25
6/21/95	8	0.6
6/22/95	22	2.3
6/22/95	26	2.9
6/22/95	31	3.4
6/23/95	46	5
6/23/95	52	5.7

MP-8		
Elapsed Time	Depth 2 feet	
0	0.0	
1	0.5	
4	1.5	
8	1.4	
22	3.6	
26	3.8	
31	4.0	
46	5.5	
52	5.5	



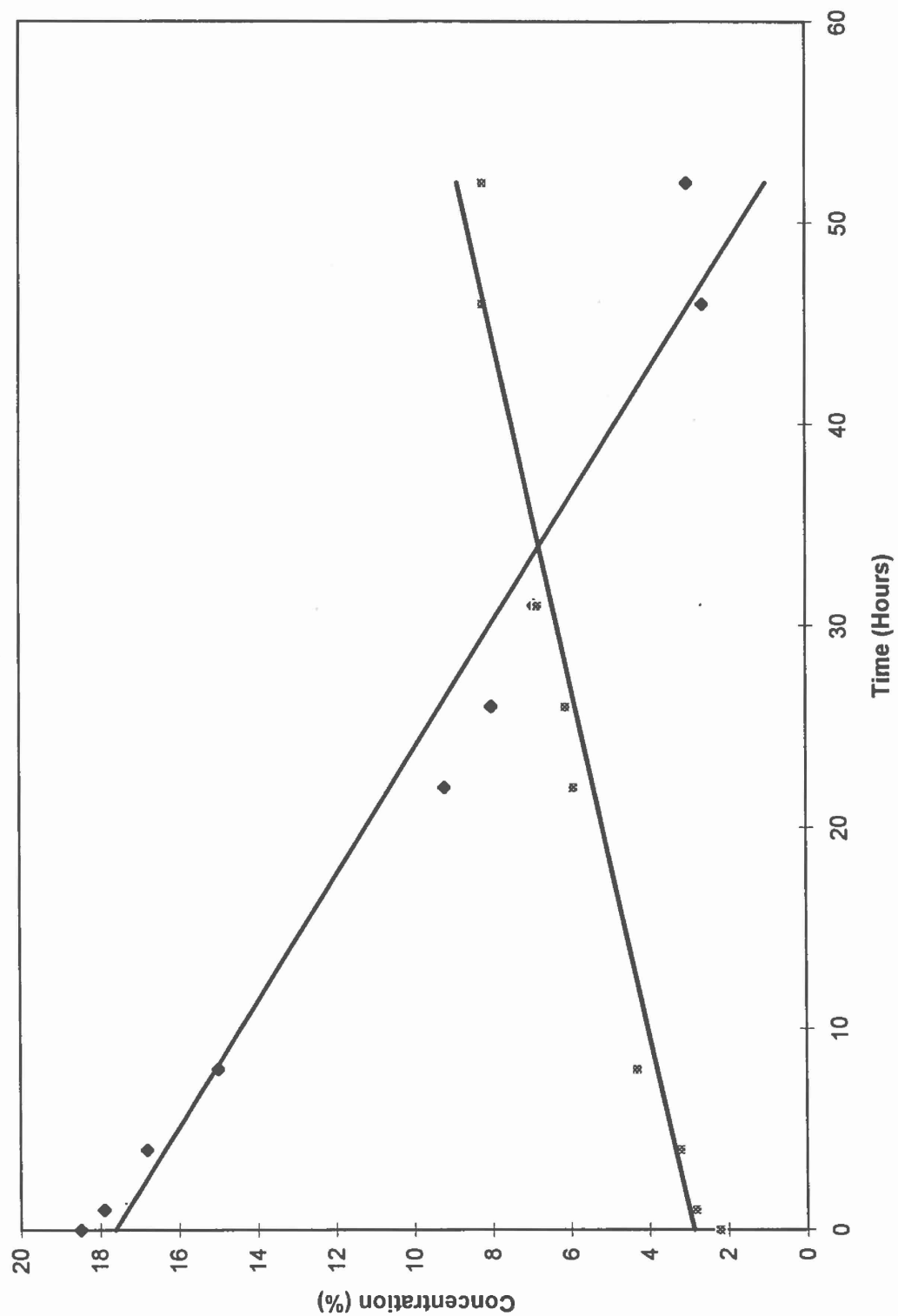
SUMMARY OUTPUT			Respiration Test #3		
			MP-1 @ 2 feet		
<i>Regression Statistics</i>					
Multiple R	0.90925238				
R Square	0.82673989				
Adjusted R Square	0.801988446				
Standard Error	0.879181496				
Observations	9				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	25.81816817	25.81816817	33.40168281	0.000677654
Residual	7	5.410720717	0.772960102		
Total	8	31.22888889			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	11.23398037	0.447548733	25.1011332	4.06436E-08	10.17569654
X Variable 1	0.09260093	0.016022533	5.779418899	0.000677654	0.054713687
<i>Upper 95%</i>	<i>ower 95.000</i>	<i>Upper 95.000%</i>			
12.2922642	10.17569654	12.2922642			
0.130488173	0.054713687	0.130488173			

Oxygen and Carbon Dioxide at MP-1 at 2 Feet  
June 21 through 23, 1995



SUMMARY OUTPUT		Respiration Test #3			
		MP-2 @ 2 feet			
<i>Regression Statistics</i>					
Multiple R	0.997196952				
R Square	0.994401762				
Adjusted R Square	0.993282114				
Standard Error	0.40859401				
Observations	7				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	148.2738261	148.2738261	888.1381056	7.9777E-07
Residual	5	0.834745324	0.166949065		
Total	6	149.1085714			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	18.26471942	0.229989628	79.41540497	5.9985E-09	17.67351323
X Variable 1	-0.386446043	0.012967272	-29.80164602	7.9777E-07	-0.419779422
	<i>Upper 95%</i>	<i>Lower 95.000</i>	<i>Upper 95.000%</i>		
	18.85592562	17.67351323	18.85592562		
	-0.353112664	-0.419779422	-0.353112664		

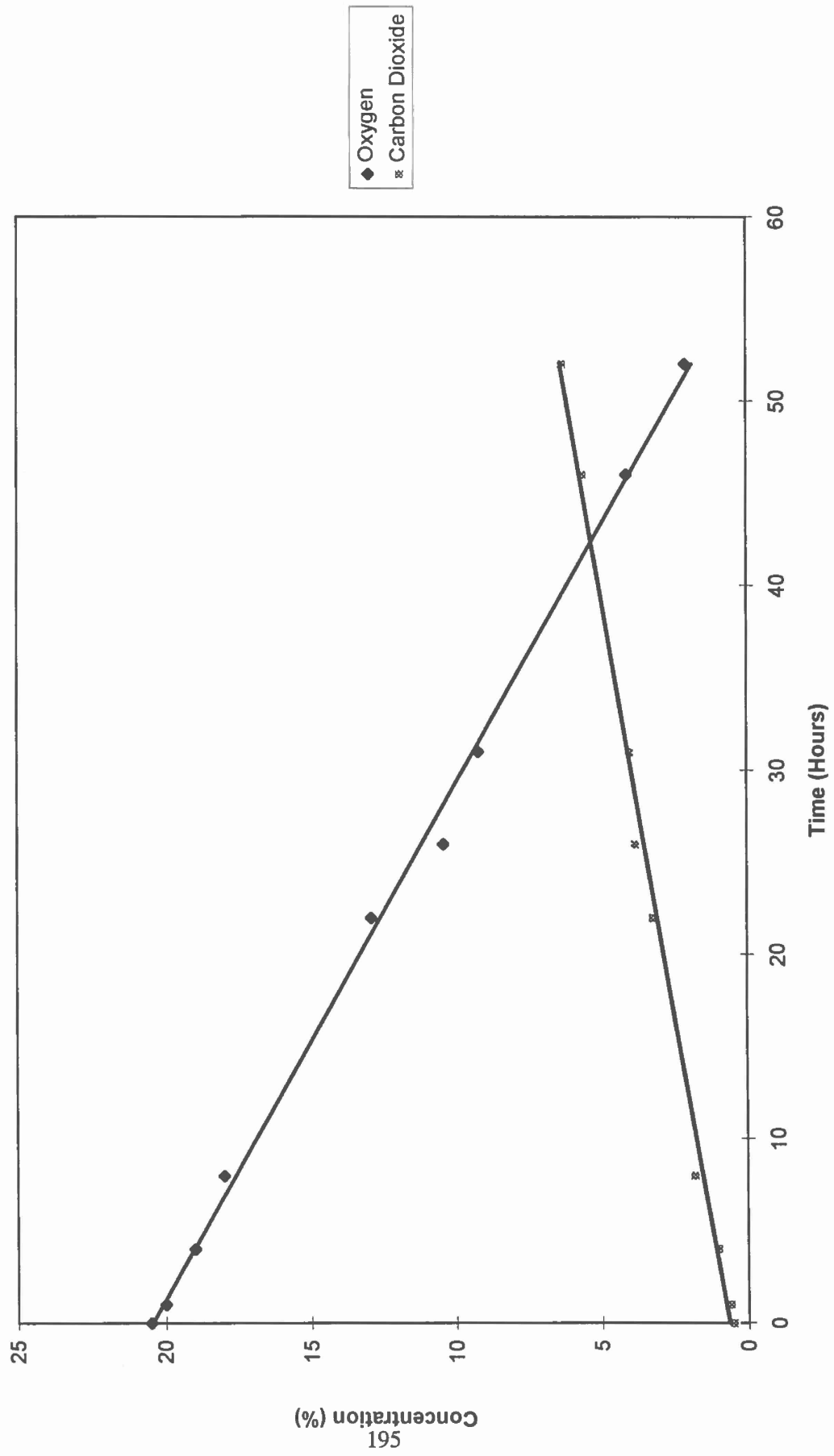
Oxygen and Carbon Dioxide at MP-2 at 2 Feet  
June 21 through 23, 1995



◆ Oxygen  
× Carbon Dioxide

SUMMARY OUTPUT		Respiration Test #3			
		MP-3 @ 2 feet			
<i>Regression Statistics</i>					
Multiple R	0.998319079				
R Square	0.996640983				
Adjusted R Square	0.996081147				
Standard Error	0.377031701				
Observations	8				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	253.0658326	253.0658326	1780.236821	1.18586E-08
Residual	6	0.852917419	0.142152903		
Total	7	253.91875			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	20.49676129	0.199000119	102.9987387	5.64505E-11	20.00982518
X Variable 1	-0.361406452	0.008565585	-42.19285273	1.18586E-08	-0.382365698
<i>Upper 95%</i>	<i>Lower 95.000</i>	<i>Upper 95.000%</i>			
20.9836974	20.00982518	20.9836974			
-0.340447206	-0.382365698	-0.340447206			

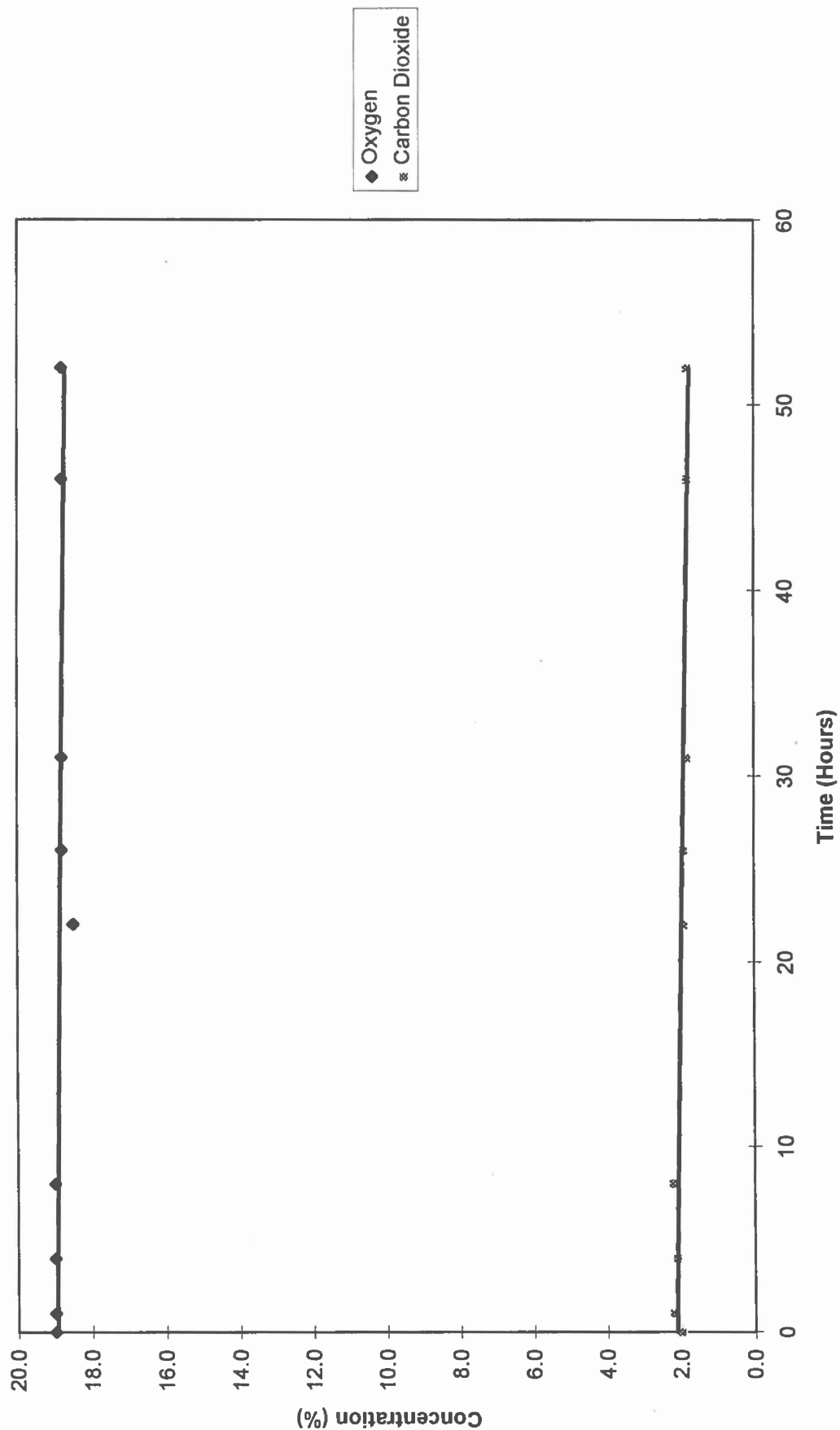
Oxygen and Carbon Dioxide at MP-3 at 2 Feet  
June 21 through 23, 1995





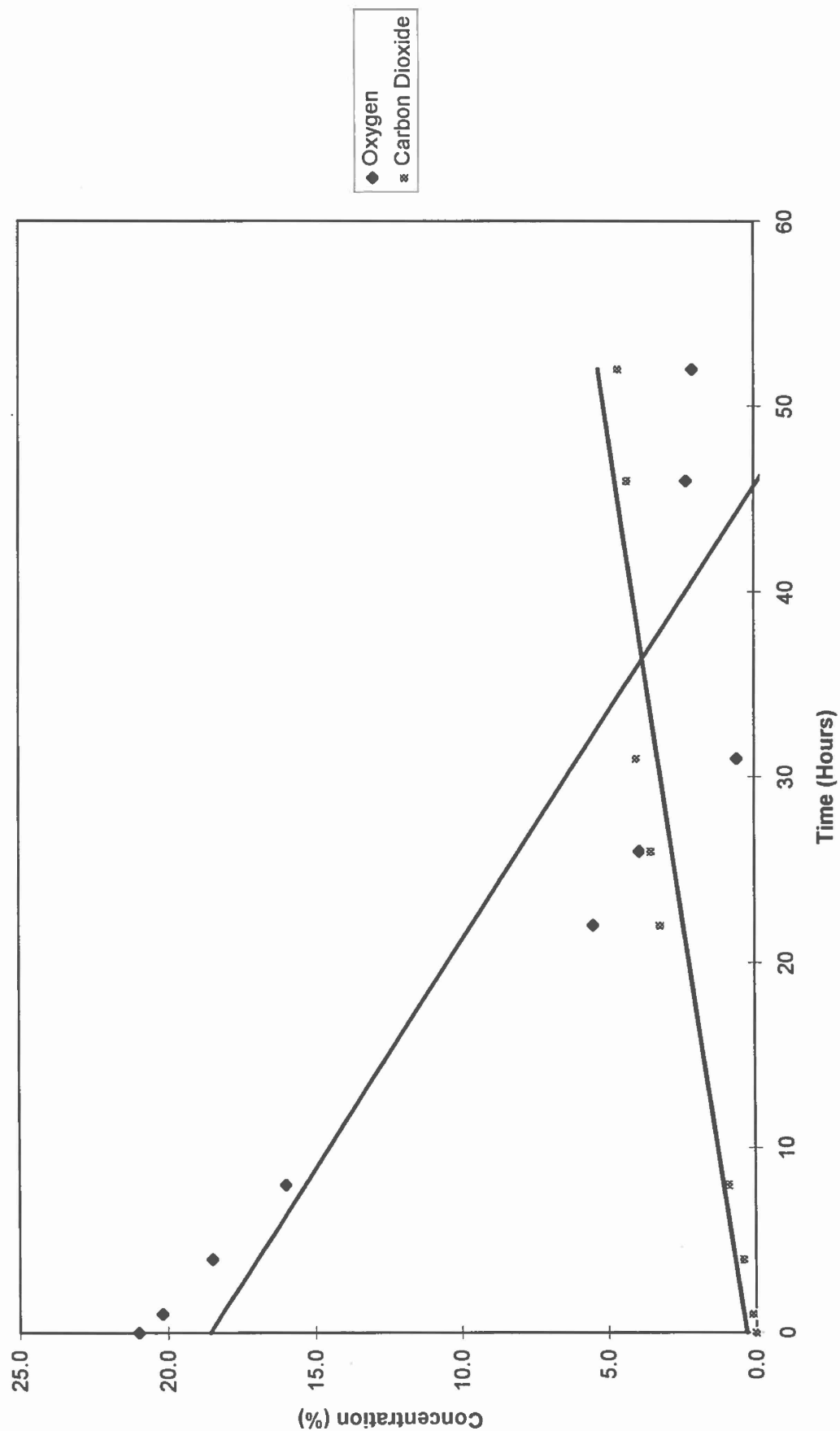
SUMMARY OUTPUT		Respiration Test #3			
		MP-5 @ 2 feet			
<i>Regression Statistics</i>					
Multiple R	0.562713946				
R Square	0.316646985				
Adjusted R Square	0.219025126				
Standard Error	0.147287971				
Observations	9				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	0.070365997	0.070365997	3.243607398	0.114716132
Residual	7	0.151856226	0.021693747		
Total	8	0.222222222			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	18.95761311	0.074977175	252.8451234	3.99618E-15	18.78032039
X Variable 1	-0.00483431	0.002684231	-1.801001776	0.114716132	-0.011181499
	<i>Upper 95%</i>	<i>Lower 95.000</i>	<i>Upper 95.000%</i>		
	19.13490583	18.78032039	19.13490583		
	0.001512888	-0.0111815	0.001512888		

Oxygen and Carbon Dioxide at MP-5 at 2 Feet  
June 21 through 23, 1995



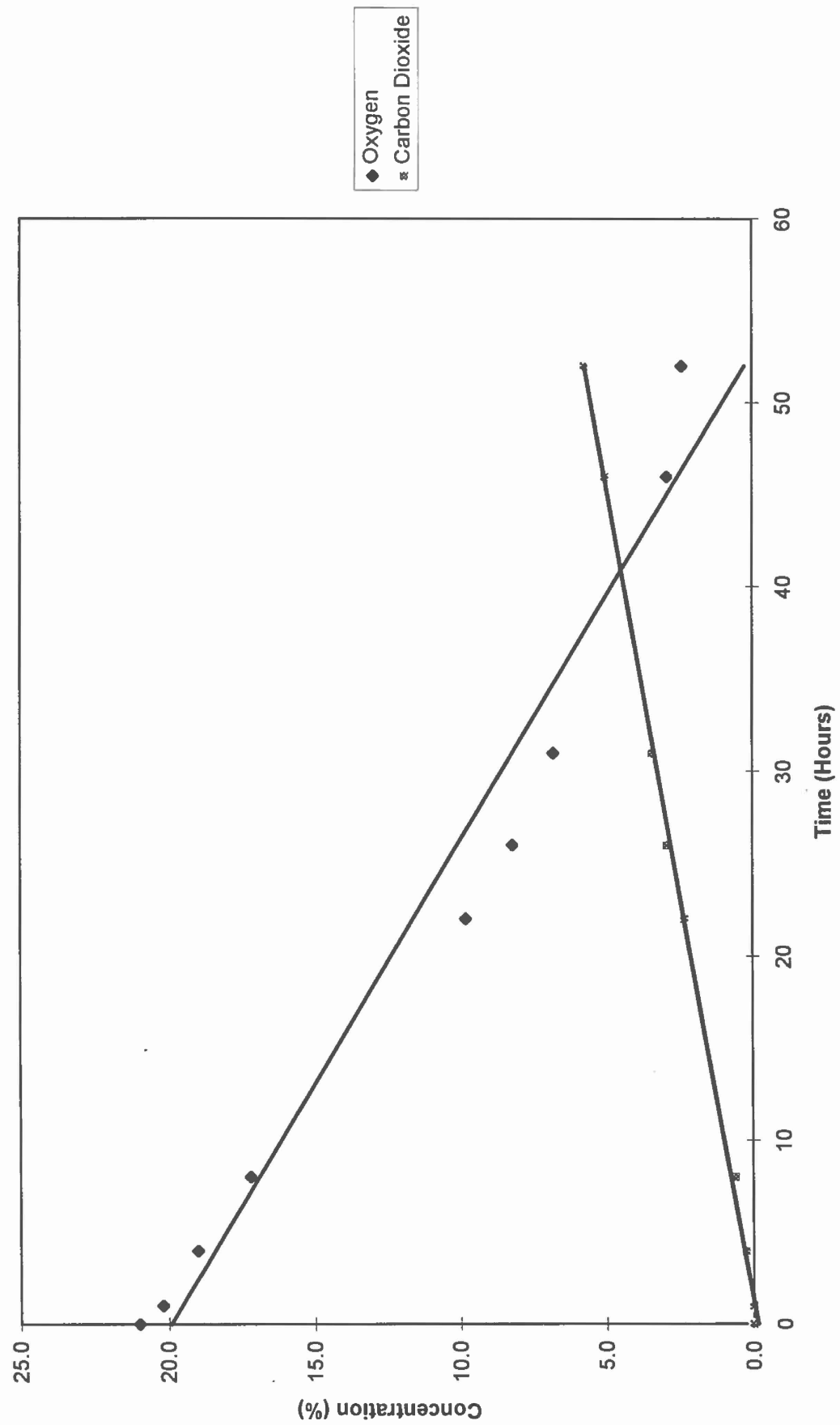
SUMMARY OUTPUT			Respiration Test #3		
			MP-6 @ 2 feet		
<i>Regression Statistics</i>					
Multiple R	0.998842593				
R Square	0.997686526				
Adjusted R Square	0.996915368				
Standard Error	0.35				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	158.4845	158.4845	1293.75102	4.72593E-05
Residual	3	0.3675	0.1225		
Total	4	158.852			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	21.16625	0.207985126	101.7680949	2.09163E-06	20.50434788
X Variable 1	-0.70375	0.019565595	-35.96875061	4.72593E-05	-0.766016513
<i>Upper 95%</i>	<i>ower 95.000</i>	<i>Upper 95.000%</i>			
21.82815212	20.50434788	21.82815212			
-0.641483487	-0.766016513	-0.641483487			

Oxygen and Carbon Dioxide at MP-6 at 2 Feet  
June 21 through 23, 1995



SUMMARY OUTPUT		Respiration Test #3			
		MP-7 @ 2 feet			
<i>Regression Statistics</i>					
Multiple R	0.9978028				
R Square	0.995610428				
Adjusted R Square	0.994732514				
Standard Error	0.442742272				
Observations	7				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	222.2998964	222.2998964	1134.063262	4.34127E-07
Residual	5	0.980103597	0.196020719		
Total	6	223.28			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	20.81893525	0.249211021	83.5393843	4.6578E-09	20.17831897
X Variable 1	-0.47317986	0.014051012	-33.67585577	4.34127E-07	-0.509299074
	<i>Upper 95%</i>	<i>Lower 95.000</i>	<i>Upper 95.000%</i>		
	21.45955153	20.17831897	21.45955153		
	-0.437060639	-0.50929907	-0.437060639		

Oxygen and Carbon Dioxide at MP-7 at 2 Feet  
June 21 through 23, 1995



SUMMARY OUTPUT		Respiration Test #3			
		MP-8 @ 2 feet			
<i>Regression Statistics</i>					
Multiple R	0.987544846				
R Square	0.975244822				
Adjusted R Square	0.971118959				
Standard Error	0.897319785				
Observations	8				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	190.3239032	190.3239032	236.3735344	4.78544E-06
Residual	6	4.831096774	0.805182796		
Total	7	195.155			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	19.53148387	0.473612017	41.23941785	1.35961E-08	18.37259617
X Variable 1	-0.31341935	0.020385736	-15.3744442	4.78544E-06	-0.363301489
	<i>Upper 95%</i>	<i>Lower 95.000</i>	<i>Upper 95.000%</i>		
	20.69037158	18.37259617	20.69037158		
	-0.26353722	-0.36330149	-0.26353722		

Oxygen and Carbon Dioxide at MP-8 at 2 Feet  
June 21 through 23, 1995

